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LEVEL II

DEVELOPMENT OF A DYNAMIC MODEL FOR ANALYSIS AND PLANNING OF LIFE-CYCLE COSTS FOR NAVY MISSILE PROGRAMS. Vol. I.

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FORWORD

This document is the final report of work ~~accomplished under Contract No. N0014-77-C-0047,~~ Development of a Dynamic Model for Analysis and Planning of Life-Cycle Costs for Navy Missile Programs. This report is in two parts. Volume I consists of the text of the report together with Appendix A, the Cost-Estimating Relationships used. Volume II contains Appendix B, a documented listing of the model equations.

The authors of this report would like to acknowledge the staff of NWS Yorktown for the information and insights regarding Navy air-launched missile operations and support, and also the staff of OP-96D, particularly Cdr. Rolf H. Clark, Mr. Carl Wilbourn and Lt. Cdr. Bruce Miller, for their valuable assistance in model development and in preparation of this report.

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Mr. Carl Wilbourn, CNO/OP-96D4

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EXECUTIVE SUMMARY

INTRODUCTION

The objective of the effort described in this report was to develop and demonstrate the feasibility of an analytic technique with the following capabilities:

i. For Navy air-launched missiles, generate estimates for operating and support and life-cycle costs based on cost driving factors such as reliability and maintainability characteristics, and

ii. Conduct trade-off analyses between cost driving factors, operating and maintenance concepts, life-cycle costs, and readiness in terms of likely availability.

This objective has been reached by developing a life-cycle simulation model consisting of three sectors: Research, Development, Test and Evaluation (RDT&E), Procurement, and Operations and Support (O&S) and by using the demonstration model to simulate the evolving program life-cycle and the accumulation of program costs. A simulation approach was chosen based on three broad problem characteristics. First, conditions within each phase of the missile system life-cycle are determined by the complex interaction of many factors. For example, procurement costs are dependent upon the rate of production, fixed and variable direct and overhead costs, and the effect of the cost improvement curve, among others. Second, the phases are dependent upon each other over time, e.g., the timing and decisions of RDT&E can greatly impact the Procurement phase. And third, the activities and costs of each phase, especially O&S, can be greatly influenced not only by physical characteristics of the missile but by a variety of managerial decisions on policies such as maintenance concepts. Mathematical treatment of such issues requires a highly flexible approach. Techniques requiring stringent assumptions such as linearity or disallowance of delays are not

suitable for analysis of this problem. Simulation, having few mathematical limitations, was considered to offer the most promising approach. Specifically, the system dynamics simulation approach and methodology were selected because of previous successful treatment of problems with similar structure, complexity, and sensitivity to managerial actions.

Another consideration that led to the selection of system dynamics was the ready access to the highly developed and easily used DYNAMO simulation language and software package that is generally used to quantify and computationally implement models based on the system dynamics methodology. The DYNAMO language has been specifically developed and tailored for simulation of systems consisting of many states, rates of change, and information fed back through an information network. DYNAMO is expressly designed for ease of use and accessibility to those with a minimum of computer knowledge. Moreover, the DYNAMO software package is oriented to quickly and easily addressing system dynamics models with "what if...?" questions such as "What would be the impact on O&S costs and readiness levels if reliability were improved?" or "What if the maintenance philosophy were changed?". Such alternative cases can be readily addressed by typing a single line or two on a computer terminal.

MODEL STRUCTURE

The life-cycle cost estimation model that has been developed is composed of three interdependent sectors: Research, Development, Test and Evaluation, Procurement, and Operations and Support. In addition to the phase specific cost calculations, each sector provides essential inputs for cost estimation to other sectors. An overview of the model is provided in Figure 1.

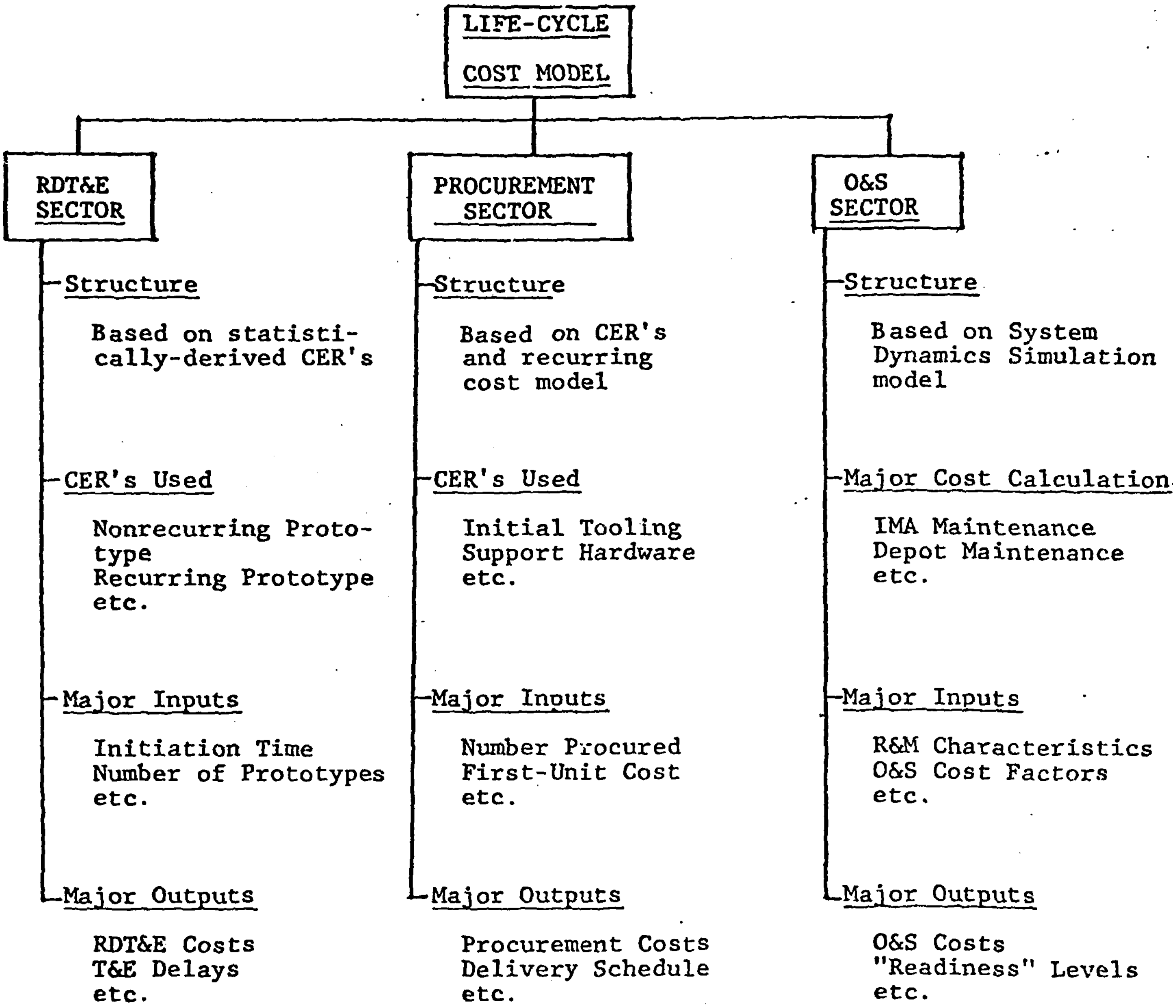

FIGURE 1. Life-Cycle Cost Model Overview

The RDT&E sector calculates the pattern of spending and total costs which are incurred in design, development, and testing of the missile. Statistically derived cost-estimating relationships (CER's) calculate the estimates for the missile RDT&E cost components of nonrecurring prototype, recurring prototype, support equipment, data, testing and evaluation, and systems engineering/program management costs. The formulation of these CER's is quite general as they have been developed to be applicable to all Navy air-launched missile programs. The user may specify delays in either TECHEVAL or OPEVAL. In these cases, additional costs are incurred and there is a different pattern of expenditures calculated for the RDT&E phase and procurement is delayed.

The procurement sector of the model calculates nonrecurring and recurring procurement costs as well as pilot production costs. The model distributes each of these costs in a spending profile over time. Nonrecurring procurement costs are calculated for the major categories of initial tooling, support hardware, spares, and aggregate support.

The O&S sector estimates the direct O&S costs, broken down by budget category, of operating and supporting a Navy air-launched missile system. The O&S sector does this by simulating the many activities involved in missile operations and support and adding up the costs associated with these activities over the service lifetime. Figure 2 illustrates the activities, flows, inventories, and O&S cost calculations included in the O&S sector. The major inputs to the O&S sector are of four basic types. These are the procurement inputs, missile reliability and maintainability characteristics, O&S cost factors, and O&S policies.

Calculated O&S cost estimates include handling and inspection, operational training, intermediate maintenance, depot maintenance, supply

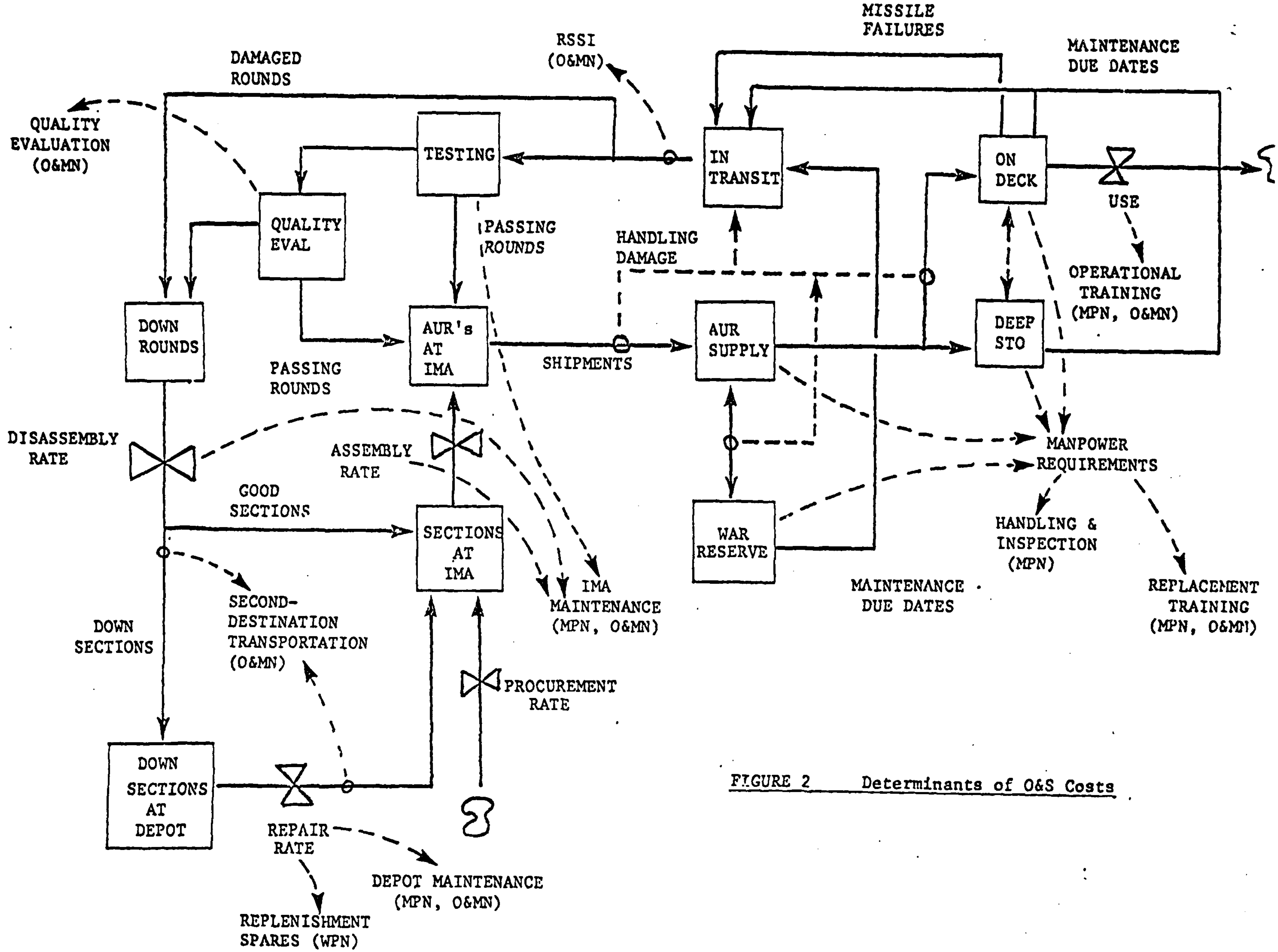

FIGURE 2 Determinants of O&S Costs

support, quality evaluation, second destination transportation, receipt, segregation, storage and issues, replacement training and replenishment spares.

In addition to cost estimates, readiness estimates are calculated by the O&S sector in order to provide a more accurate picture of the "services" provided, in terms of missile availability. This overall picture of life-cycle costs versus readiness is essential in comparing alternative cases. A missile with low reliability and maintainability will generate both high O&S costs and low readiness levels. But on the other hand, a higher level of spending (for example, to obtain a better design, or on preventive maintenance) may raise readiness levels. Several basic measures of readiness are calculated within the O&S sector to provide means for comparing alternative cases and potential trade-offs of this type. These readiness measures are based on the number of missiles which are available for operations and on their reliability characteristics. The first, simplest measure of readiness is merely the number of all-up rounds which are available to the fleet. This is the same as the number of missiles which are <u>not</u> undergoing maintenance or in transit to or from the fleet. A related measure is the fraction of missiles in the O&S system which are available to the fleet relative to the total number of missiles. This "percentage readiness" discounts the impact of simply procuring more missiles to increase the number available. A truly accurate picture of missile hardware readiness, however, is not reflected by a simple enumeration of the number of missiles available to the fleet. If the missile's reliability is low, many of those available missiles will be useless. Such factors are taken into account in calculating another definition of readiness, the number of all-up rounds "likely to be ready". For this measure, the numerical readiness is adjusted by the rates

of handling damage, shelf-life failure, and aircraft avionics/BIT-indicated failure experienced. As before, this can be compared to the total number of rounds in the O&S system to obtain a measure of "percentage likely readiness". These "likely readiness" measures indicate not only the availability of missiles, but also the efficiency of the missile design and O&S system in providing ready missiles. Finally, a measure of "total life-cycle hardware readiness" is included for comparison with total life-cycle costs. To obtain this measure, the number of all-up rounds likely to be ready is accumulated over the course of the missile program life cycle. Each missile which is likely to be ready for one year adds one missile-year to the total life-cycle hardware readiness level. It is this measure which is most appropriate in comparing readiness and life-cycle costs for alternative designs or support concepts.

These readiness measures are, of course, simply formulated. They do not take into account how the missile will perform in its intended combat role. The readiness estimates calculated by the O&S sector do, however, provide a means for comparing alternative costs according to specific readiness criteria. As more complete readiness measures are developed, they can be implemented within the model.

To summarize, then, the life-cycle cost estimation model as described has the following capabilities:

i. Calculates an estimate of annual program spending by life-cycle phase and budget category;

ii. Cumulates annual program expenditures into an estimate for overall direct life-cycle costs;

iii. Calculates annual expenditures and life-cycle cost for alternative procurement rates, reliability and maintainability characteristics, and operations policies; and

iv. Calculates trade-offs between life-cycle costs, reliability and maintainability, operating and maintenance concepts, and readiness.

The model has been applied to develop a benchmark base case forecast and alternative projections investigating i) an alternative maintenance concept, ii) different reliability and maintainability characteristics, and iii) delays occurring during T&E. A number of sensitivity analyses have also been performed with the model. The following section describes several applications of the model in order to demonstrate model functioning, required inputs, and calculated output.

EXAMPLE APPLICATIONS

The benchmark base case projection is based upon a set of specific characteristics representative of an "average air-launched missile", and not upon any particular missile program. Thus, the cost estimates presented and the results of the analyses performed are illustrations of the types of analyses which can be done with the model, not forecasts or analyses of a specific program. Applications to a specific program would require program specific input characteristics and modification and refinement of some cost equations.

All cost estimates presented are given in terms of constant (FY77) dollars although the model also calculates cost in current dollars.

The major base case input assumptions are summarized in Table 1. When provided with these inputs, the model generates estimates of life-cycle costs, spending profiles, and readiness levels. The overall profile of the base case projected missile program spending is illustrated in Figure 3. The R&D program begins in 1975, and estimated R&D spending rises quickly to about $20 million per year in 1976. At the end of 1977, pilot production

BASE CASE INPUTS

- 4-Year RDT&E program, with no delays
- 120 Pilot production models, 40 allocated to RDT&E
- 3000 Full-scale production missiles, procured over a span of 5 years
- Recurring procurement cost elements:

First-unit direct costs	$ 84K
Other direct unit costs	$ 5K
Fixed overhead costs	$ 27M
Other business base	$ 12M
Variable overhead rate	50%
Fixed direct costs	$288K

- Operations and support policies:
  - 40 Training firings per year
  - "Fly-until-die", not "rotation", at organizational level
  - Maintenance Due Dates are every 2 years at organization, 5 years in reserve deep storage
  - 85% Reparables and consumables supply availability
- Reliability and maintainability parameters:

2%	Handling damage rate
5%	Rounds fail after 2 years at organization
10%	Rounds fail after 5 years in reserve
10%	Avionics/BIT "no-go" indication rate
40	Manhours to repair average "down" missile section

TABLE 1, Base Case Inputs

PAGE 85 FILE COMB 8/23/77 12:17 BASE

RDS=R,TIPRS=P,TOSC=O,THSS=T

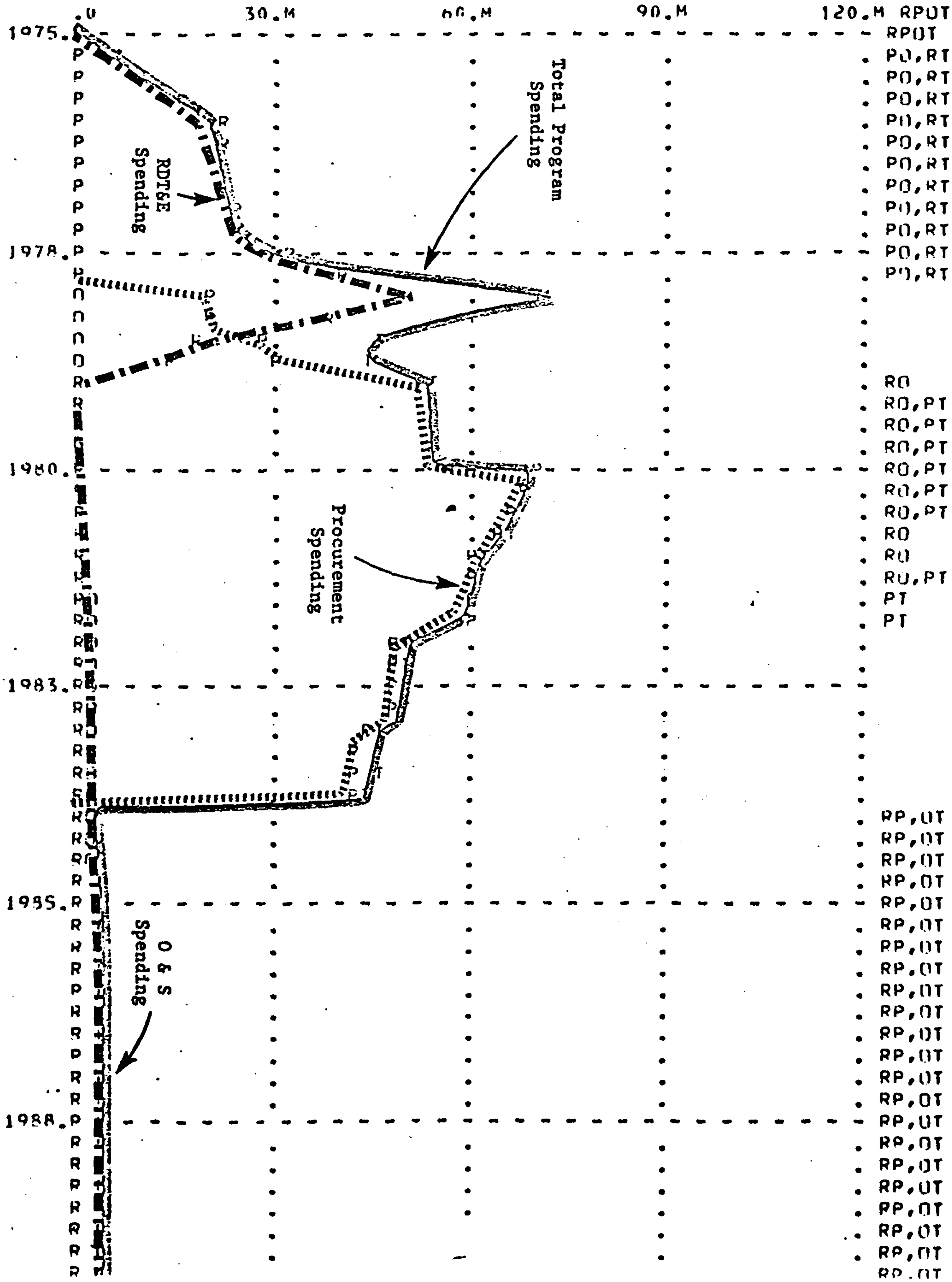

FIGURE 3. Spending Profile

is begun. The large peak in spending at this time is caused by expenditures for initial tooling and test equipment. Full-scale production begins in 1979 and extends for five years, through 1983. During this period, procurement spending is calculated to be on the order to $40 to $70 million annually. Finally, as the missiles are deployed, estimated O&S spending begins to rise. As reflected in the model output shown in Figure 3, O&S spending for air-launched missiles is only a small fraction of total program spending. Table 2 presents the base case life cycle costs by major categories. Table 3 gives the estimates for annual O&S spending components for the representative year of 1990.

The level of readiness achieved for the base case is also provided. Over the life of the missile program through 1990, the base case projects 16,637 missile-years of total life-cycle hardware readiness. This is the cumulative number of all-up rounds "likely to be ready" over the time horizon. The percentage likely readiness in the representative year 1990 is 75.6%. These two readiness measures are calculated based on the likelihood of successful missile checkout, allowing for the chances of handling damage, failure on the shelf, and indicated failure of avionics or built-in (BIT) tests.

SENSITIVITY ANALYSES

In addition to the base case outlook, the model has been used to investigate numerous alternative cases. In these cases, it is shown that missile reliability and maintainability characteristics may have a significant effect on readiness and on O&S costs. Changes in total life-cycle costs are relatively small, however, simply because O&S costs are such a small fraction of total costs for the missile program. For the "average" missile represented in the base case, in increasing order of importance,

BASE CASE LIFE-CYCLE COSTS

Cumulative Cost Through 1990

Total Life-Cycle Cost ($M)	$405.34		
RDT&E		$90.48	
Non-Recurring Prototype			31.59
Recurring Prototype			2.43
Support Equipment			8.65
T&E			7.09
Data			2.69
Program Management			7.91
Pilot Production Costs			30.12
Procurement		$290.09	
Pilot Production Costs			15.33
Non-Recurring Production			70.53
Recurring Production			204.23
O&S		$24.78	
MPN			9.97
O&MN			13.73
WPN			1.08

TABLE 2. Base Case Life-Cycle Costs

BASE CASE ANNUAL O&S SPENDING

Annual O&S Costs (000 $77) in 1990		MPN	O&MN	WPN
Handling & Inspection		800		
Operational Training		40	160	
IMA		154	738	
Depot			552	
Supply Support			18	
Quality Evaluation			192	
Transportation			13	
RSSI			68	
Replacement Training		250	124	
Spares				128
Total	$3236	1243	1865	128

TABLE 3. Base Case Annual O&S Spending

increases in the handling damage rate, the shelf life failure rate, and the avionics/BIT "no-go" indication rate have a negative impact on missile readiness. Their impact on O&S and total life-cycle costs, however, is in the reverse order. Thus, an avionics/BIT "no-go" indication rate has a large impact on readiness but only a minor impact on costs, while the handling damage rate affects costs much more relative to its impact on readiness. Missile maintainability may not have much effect on readiness, if there are no constraints in committing resources to missile maintenance, but it does have a sizable impact on costs.

A policy of rotating the missiles at the organizational level has only a minor effect, decreasing readiness marginally while costing slightly more. As would be expected, 100% supply availability increases both readiness and costs, but only slightly. The maintenance due date policy is seen to be a more important determinant of life-cycle costs and readiness. For the missile represented by the base case assumptions, more frequent periodic maintenance adds significantly to costs and actually decreases readiness. However, in an alternative case addressed by the model, more frequent periodic maintenance may improve readiness when the missile has a poor shelf life performance. This result emphasizes the importance of analyzing how well the missile maintenance concept is tailored to the specific physical characteristics of the missile.

Table 4 presents, in summary form, a review of the results of the major independent sensitivity analyses which have been conducted with the cost-estimating model. For each analysis, the changes in life-cycle readiness and in the major categories of life-cycle costs are listed. The analyses are presented in three groups, dealing with i) RDT&E and procure-

SENSITIVITY ANALYSES

% Change From Base

Analysis	Life-Cycle Readiness	Life-Cycle Costs: Total	RDT&E	Procurement	O&S
RDT&E & Procurement					
T&E Delays	-14	4	19	0.4	-7
Procurement Stretched Out	-11	2	0	4	-5
Business Base	0	-6	0	-8	-0.4
Degraded R&M					
BIT/Avionics "No-Go"	-12	0.3	0	0	5
Shelf Life	-7	0.7	0	0	11
Handling Damage	-3	1.1	0	0	18
Maintainability	0	0.9	0	0	15
O&S Policies					
Rotation	-0.03	0.1	0	0	2
100% Supply	2	0.1	0	0	1
Annual MDD	-3	2	0	0	32
Combinations					
Degraded Reliability	-21	2	0	0	36
Degraded R&M	-21	4	0	0	62
T&E Delays, Procurement Stretched Out	-25	6	19	4	-12

TABLE 4. Sensitivity Analyses

ment (T&E Delays, Procurement Stretched Out, and Increased Other Business Base), ii) the reliability and maintainability characteristics of the missile (Avionics/BIT "No-Go" Rate, Shelf Life, Handling Damage, and Maintainability), iii) alternative operations and support policies (Rotation at the organizational level, 100% Supply Availability, and Annual Maintenance Due Date) and iv) combinations of factors.

Extensive sensitivity analyses of the RDT&E and procurement sectors have not been conducted simply because these sectors of the model are based in large part upon cost-estimating relationships and formulations already familiar to OP-96D. The analyses presented here do, however, emphasize importance of RDT&E and procurement costs in total life-cycle costs. For a Navy air-launched missile program, these are likely to amount to over 90% of total life-cycle costs. Delays in RDT&E, rescheduling out of procurement, and changes in procurement cost factors have a significant impact on total life-cycle costs. Furthermore, a slippage in program schedule results in a period of time in which there are fewer missiles available for use, thus reducing total life-cycle hardware readiness.

In the O&S sphere, the handling damage and shelf life failure rates, particularly in conjunction with the maintenance philosophy in use, are crucial factors underlying O&S costs. Other missile reliability characteristics, such as the avionics/BIT "no-go" indication rate, will have more of an impact on readiness but less on total costs.

FUTURE ACTIVITIES

The following activities are currently being undertaken. First, the technique is being modified with carefully developed inputs and cost equations for a specific Navy air-launched missile program. This will

provide several major and immediate benefits. It enables the estimates generated by the technique to be compared for validity purposes with existing estimates based largely on subjective interpretations of past experiences. The quantification will provide insights into data collection requirements and difficulties. Finally, this step will enable the program manager to investigate trade-offs that otherwise were virtually impossible. Second, a training program in the use and modification of the technique is being prepared. This program will be presented to OPNAV analysts so that the technique will become an effective and efficient in-house tool.

Finally, a similar cost estimation technique for Navy aircraft programs is being developed. This will focus on the much more complex aircraft O&S system, the multitude of costs involved, and, because of the much larger O&S costs, the significant design and operating trade-offs available to program managers.

I. INTRODUCTION

The objective of the effort described in this report was to develop and demonstrate the feasibility of an analytic technique with the following capabilities:

i. For Navy air-launched missiles, generate estimates for operating and support and life-cycle costs based on cost driving factors such as reliability and maintainability characteristics, and

ii. Conduct trade-off analyses between cost driving factors, operating and maintenance concepts, life-cycle costs, and readiness.

This objective has been reached by developing a life-cycle simulation model consisting of three sectors: Research, Development, Test and Evaluation (RTD&E), Procurement, and Operating and Support (O&S), and by using the demonstration model to simulate the evolving program life-cycle and the accumulation of program costs. The simulation approach and methodology selected for modeling the life-cycle and structuring the integration was that of system dynamics.[1] This approach was chosen based on two broad considerations: i) the existence of strong compatibilities between the methodology and major characteristics of the problem and ii) ready access to DYNAMO, the powerful and easily used simulation language and software package used to implement system dynamics models.

A system dynamics simulation approach was chosen based on several major characteristics of the life-cycle cost problem. Conditions within each phase of the missile system life-cycle are determined by the complex interaction of many factors. For example, procurement costs are dependent upon the rate of production, fixed and variable direct and overhead costs,

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[1]Basic references include Industrial Dynamics, J.W. Forrester, M.I.T. Press, 1961. and The Dynamics of Research and Development, E.B. Roberts, Harper and Row, 1964.

and the effect of the cost improvement curve, among others. The phases also are dependent upon each other over time, e.g., the timing and decisions of RDT&E can greatly impact the Procurement phase. In addition, the activities and costs of each phase, especially O&S, can be greatly influenced not only by physical characteristics of the missile but by a variety of managerial decisions on policies such as maintenance concepts. Mathematical treatment of such issues requires a highly flexible approach. Techniques requiring stringent assumptions such as linearity or disallowance of delays are not suitable for analysis of this problem. Simulation, having few mathematical limitations, was considered to offer the most promising approach. Specifically, the system dynamics simulation approach and methodology were selected because of previous successful treatment of problems with similar structure, complexity, and sensitivity to managerial actions.

The system dynamics methodology views a system as composed of three components: states of the system, rates of change, and information networks. States are the condition of the system and are accumulations of system resources. These resources include, for example, inventories, people, money, capital equipment, and orders. Rates of change are the flows of the system such as receipt and shipment of goods, arrival and departure of people, receipt and payment of money, and acquisition and disposal of capital equipment. The information networks are the means by which information is collected disseminated throughout the system. These may be either formal management information systems or informal perceptions and data collection. System dynamics models reflect this multi-component view of a system by incorporating three primary types of equations. First, equations that calculate the rates of change of system states based on information describing past and current

states of the system, second, equations that update the system states to the next point in time using calculated rates, and third, equations representing the flow of information. During model operation, the rate equations calculate rates of change at the current point in time, the state equations use the calculated rates to update the system states, and then, the updated state values enter the information flow equations and are used to determine the rates of change over the next time period. This calculation process is performed repeatedly, and in this manner, a system dynamics model sequentially steps forward, simulating a system's movement through time. Equation development and quantification includes explicit representation of the many delays embodied in an actual situation so that realistic simulation results are achieved. This capability of representing progression through time permits the detailed treatment of programs as they move through the multiple phases of the life-cycle and through an evolving O&S phase. This was deemed a highly important requirement in the methodology selection.

The second broad consideration that led to the selection of system dynamics was the ready access to the highly developed and easily used DYNAMO simulation language and software package that is generally used to quantify and computationally implement models based on the system dynamics methodology. Theoretically, several computer languages might be used to simulate the O&S system. However, the DYNAMO language has been specifically developed and tailored for simulation of systems consisting of many states, rates of change, and information fed back through an information network. The language was originally developed at M.I.T. twenty years ago and has undergone continuous improvements and extensions over the years.[2] DYNAMO is expressly designed for ease of use and accessibility to those with a minimum of computer knowledge.

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[2] DYNAMO User's Manual, 5th Edition, A.L. Pugh, III, M.I.T. Press, 1977.

These benefits are provided through the use of simple, easy to read algebraic equation formats, extensive error detection capabilities, and the reporting of errors in easily understood terms. Consequently, the development of the cost estimation model using the system dynamics methodology implemented by the DYNAMO language greatly reduced software development costs and enhanced the likelihood of future utilization of the model by OPNAV analysts. Moreover, the DYNAMO software package is oriented to quickly and easily addressing system dynamics models with "what if...?" questions such as: "What would be the impact on O&S costs and readiness levels if reliability were improved?" or "What if the maintenance philosophy were changed?". Such alternative cases can be readily addressed by typing a single line or two on a computer terminal. Thus, time consuming respecification of the model is not required by the user but is quickly accomplished by the software package. These effective and efficient programming capabilities were judged to be highly valuable and strongly supported the selection of system dynamics and DYNAMO as the problem solution approach.

A brief example can further demonstrate the strong problem/methodology compatibility which exists between system dynamics and life-cycle cost analyses. Consider, for example, one state within the O&S system, the inventory of missiles at the organizational level. This state is increased over a period of time by the shipment rate of all-up rounds from supply sources and reduced by training firings, returns to repair centers for periodic maintenance, and returns due to test failure and handling damage. A system dynamics model of this sub-sector of the O&S system would include equations calculating i) returns for periodic maintenance (depending upon the number of missiles in the inventory, the age distribution of those missiles, and the periodic maintenance intervals), ii) returns due to indicated test failure (dependent upon number of missiles being testsd for flight and a failure rate), iii)

returns due to handling damage (dependent upon number being moved and frequency of damage), iv) shipment rate from the supply source (dependent upon requirements at the organizational level and availability at the supply source), and v) the updated value for the missile inventory at the organizational level based on the rates of change during the previous time period. Typically, such updated inventory values are then "fed back" to be used in the determination of a new replenishment ordering rate. For example, if the inventory of missiles at the organizational level is lower than a desired number due to abnormally high training firings, this state information is used to determine a corrective replenishment order rate to the supply source or storage magazine. This order rate then influences the shipment rate to the organization so that the desired inventory level is gradually reached. To represent this process, a system dynamics model would contain equations representing the flow of information, ordering and transportation delays, and corrective managerial ordering actions. These equations would then provide inputs to the calculation of the shipping rates from the supply source and the storage magazine. The multitude of other inventories, flows, and activities within the O&S system are also readily describable in terms of the system dynamics components: states, rates of change and an information network. This conceptual compatibility supported the selected of the system dynamics methodology.

Using this approach, a cost estimation model for Navy air-launched missile programs has been developed with the following capabilities:

i. Calculates an estimate of annual program spending by life-cycle phase and budget category;

ii. Cumulates annual program expenditures into an estimate for overall direct life-cycle cost;

iii. Calculates annual expenditures into an estimate for alternative procurement rates, reliability and maintainability characteristics, and operations policies; and

iv. Calculates trade-offs between life-cycle costs, reliability and maintainability, operating and maintenance concepts, and readiness.

This report describes the model in detail and presents numerous applications. Specifically, in Chapter II, an overview of the model is provided, and the research, development, test and evaluation, procurement, and O&S sectors of the model are described in detail. These three sectors of the model, each concerned with a specific phase of a missile program's life cycle, are thoroughly interdependent. Besides performing their own calculations, they provide one another with several of the essential inputs for cost estimation. Chapter III describes applications of the life-cycle cost estimation model including a benchmark base case forecast and "what-if" projections investigating an alternative maintenance concepts, different reliability and maintainability characteristics, and delays occurring during T&E. Important data and leverage points in life-cycle cost systems are identified through numerous sensitivity analyses. Chapter IV presents a summary and conclusions and indicates potential next steps and applications.

II. DESCRIPTION OF THE LIFE-CYCLE COST MODEL

2.1. INTRODUCTION

The first section of this chapter presents a broad overview of the air-launched missile life-cycle cost model, the sectors of the model, and its mode of operation. The following sections provide more detailed descriptions of the Research, Development, Testing and Evaluation (RDT&E), Procurement, and Operations and Support (O&S) sectors, and the linkages among them.

2.2. LIFE-CYCLE COST MODEL OVERVIEW

This model has been developed to provide an estimate of overall life-cycle costs and readiness levels for Navy air-launched missile programs. The model traces a program and its associated costs through the program phases of RDT&E, procurement, and operations and support. The model is specifically constructed to facilitate the assessment of alternative program policies and missile characteristics by investigating "what-if" and trade-off questions regarding cost- and readiness-driving factors in the three program phases.

As illustrated in Figure 2-1, the model consists of three integrated sectors, each concerned with a specific phase of a missile program's life cycle. Each sector is made up of a group of mathematical equations written in the DYNAMO language, a powerful, easy to use computer simulation language.

The model performs the simulation by calculations that sequentially "step forward" from one time-instant to another. At each time-step, the

LIFE-CYCLE COST MODEL

RDT&E SECTOR

- Structure

  Based on statistically-derived CER's (See Fig. 2-2)

- CER's Used

  Nonrecurring Prototype
  Recurring Prototype
  etc.
  (See Tab. A-1)

- Major Inputs

  Initiation Time
  Number of Prototypes
  etc.
  (See Tab. 3-1)

- Major Outputs

  RDT&E Costs
  T&E Delays
  etc.
  (See Tab. 2-2)

PROCUREMENT SECTOR

- Structure

  Based on CER's and recurring cost model
  (See Fig. 2-3)

- CER's Used

  Initial Tooling
  Support Hardware
  etc.
  (See Tab. A-2, A-3)

- Major Inputs

  Number Procured
  First-Unit Cost
  etc.
  (See Tab. 3-1)

- Major Outputs

  Procurement Costs
  Delivery Schedule
  etc.
  (See Tab. 2-3)

O&S SECTOR

- Structure

  Based on System Dynamics Simulation model
  (See Fig. 2-5, 2-6)

- Major Cost Calculations

  IMA Maintenance
  Depot Maintenance
  etc.
  (See Tab. A-4)

- Major Inputs

  R&M Characteristics
  O&S Cost Factors
  etc.
  (See Tab. 3-1)

- Major Outputs

  O&S Costs
  "Readiness" Levels
  etc.
  (See Tab. 2-4)

FIGURE 2.1 Life-Cycle Cost Model Overview

model calculates the costs of the activities represented by the current state of the system for the program phases of RDT&E, procurement, and O&S. Based on the calculated rates of change, it also updates the current state of the system, which will then have an impact on costs during the following time periods. For example, the action of shipping a "down" missile to the IMA (Intermediate Maintenance Activity) incurs a transportation and handling cost, and also adds to the inventory of missiles awaiting repair. As the model steps through time, it keeps track of the many spending categories and accumulates them to provide the estimate and break-down of total life-cycle costs through the end of the time horizon under consideration. The rates of spending, which are calculated in constant (1977) dollars, can be escalated to yield cost estimates in current-dollar figures. These cost and spending estimates are then output by the model, in graphical or numerical form.

The model is very flexible with regard to the amount and form of output which can be generated. Table 2-1 contains a summary of the cost outputs of the model. Flexibility inherent to the DYNAMO language permits a tabulation or plot of any model variable as part of its output with relative ease.

The following sections of this chapter describe the individual sectors of the life-cycle-cost model in detail.

2.3. RDT&E SECTOR

The RDT&E sector calculates the pattern of spending and total costs which are incurred in design, development, and testing of the missile. An overview of this sector is presented in Figure 2-2.

The major inputs to the RDT&E sector include the times at which research and development (R&D) and the phases of testing and evaluation (T&E)

TABLE 2-1. WBS of Cost Outputs

TOTAL LIFE-CYCLE COSTS

RDT&E Costs

- Missile RDT&E
  - Nonrecurring Prototype
  - Recurring Prototype
  - Support Equipment
  - Testing & Evaluation
  - Data
  - Systems Engineering/Program Management
- Pilot Production (share)

Procurement Costs

- Pilot Production (share)
- Recurring Procurement
- Nonrecurring Procurement
  - Initial Tooling & Test Equipment
  - Support Hardware
  - Spares
  - Aggregate Support
    - Support Engineering/Program Management
    - Follow-On OT&E
    - Training Services & Equipment
    - Data
    - ECP's/ECO's

O&S Costs

- Handling & Inspection
- Operational Training
- Intermediate Maintenance
- Depot Maintenance
- Supply Support
- Quality Evaluation
- Transportation
- RSSI
- Replacement Training
- Replenishment Spares

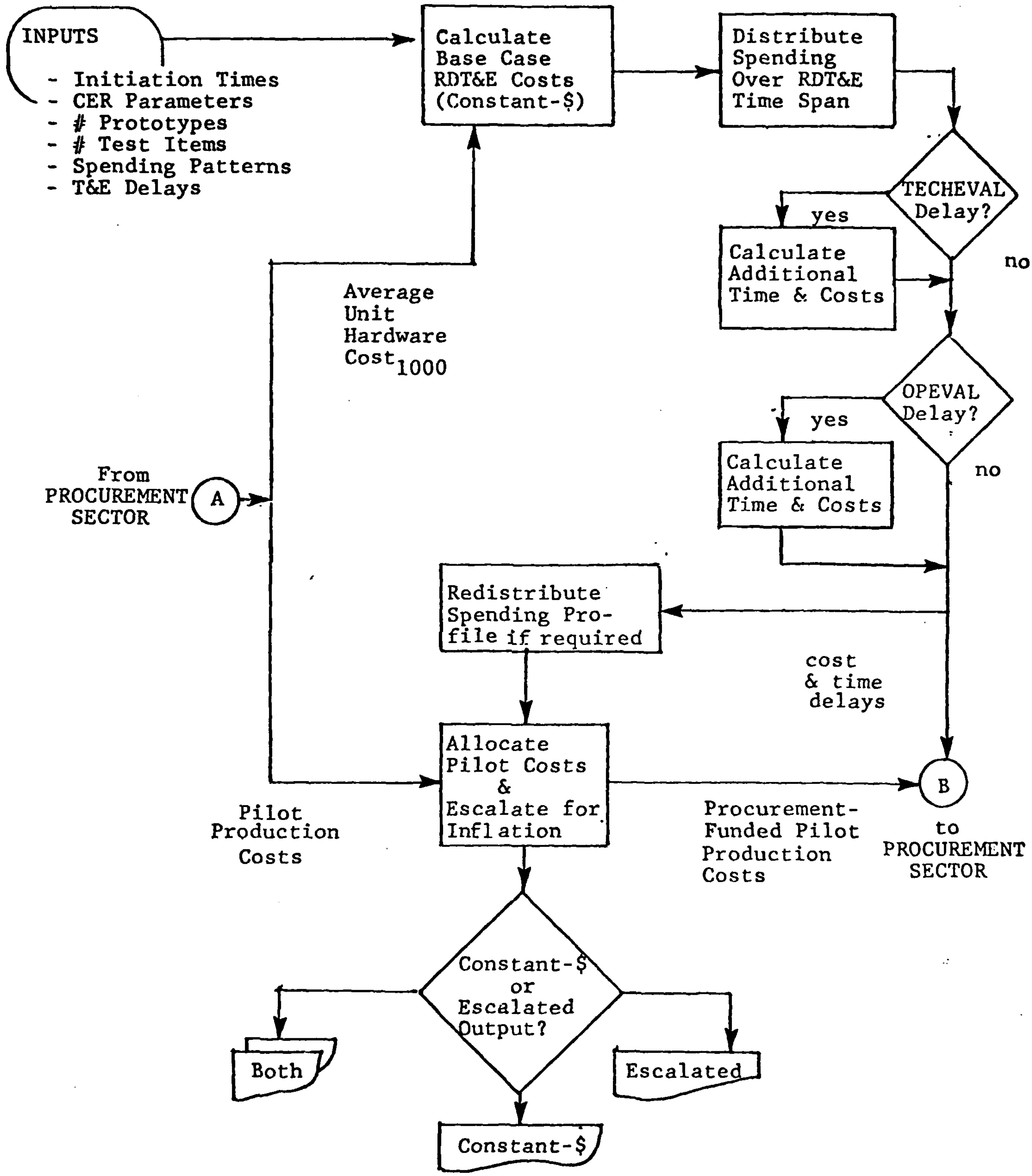

FIGURE 2.2 RDT&E Sector Overview

are initiated, the statistically-derived parameters for the cost-estimating relationships (CER's), the number of prototypes to be built and the number of test items to be supplied for T&E, the length and time-patterns of spending, and any delays which may occur in T&E. A detailed list of these inputs can be found in Table 3-1 in Section 3.1, the discussion of the base case cost estimate.

The statistically-derived CER's for the major cost elements of missile research and development have been supplied by OP-96D. These CER's calculate the estimates for the missile RDT&E cost components of nonrecurring prototype, recurring prototype, support equipment, data, testing and evaluation, and systems engineering/program management costs. The formulation of these CER's is quite general and they were developed to be applicable to all Navy air-launched missile programs. The mathematical equations for the six CER's are listed in Table A-1 in Appendix A.

Based on the inputs provided by the user and by the Procurement sector (the average unit hardware cost of the first 1000 missiles), the RDT&E sector calculates the base-case, constant-dollar RDT&E cost elements of the missile program. These costs are then distributed in a spending pattern over the time span of the RDT&E phase. If there are delays in TECHEVAL or in OPEVAL, then additional costs are incurred. In this case, there would be a different pattern of expenditures to be calculated for the RDT&E phase and procurement would be delayed. Based on the costs of pilot production estimated by the Procurement sector, the RDT&E sector then allocates these costs between the two sectors.

For each cost component, the total cost is distributed over a period of years in a pattern specified by input parameters. The patterns for the base

case are based on a qualitative examination of a number of missile R&D programs.

These historical programs have also been used to provide a mechanism for the effects of program delays on R&D costs. When delays are encountered in TECHEVAL or OPEVAL, RDT&E spending is simply stretched out, at the current rate, for the length of the delay.

The model's treatment of T&E consists of representations of the two sequential phases of TECHEVAL and OPEVAL. TECHEVAL occurs earlier in the RDT&E phases, and problems encountered then may be far more serious in their cost and schedule implications than OPEVAL problems. On the other hand, pilot production missiles are tested in OPEVAL, so that problems discovered then may have a more direct impact on the procurement phase which is already under way.

As T&E proceeds, discrepancies may be discovered between actual missile performance parameters and the performance thresholds specified by the program. These discrepancies may prompt several actions. If there is little difference between actual and desired performance, the existing missile design may be accepted, and production of a revised-capability missile will begin. Or, the planned initiation of procurement may be delayed or stretched out, while quality control is upgraded or additional R&D is conducted to correct design deficiencies.

The cost-estimating model can generate its own T&E-caused delays, based on a comparison of input parameters for the desired and actual performance parameters such as MTBF (Mean Time Between Failures) and MTTR (Mean Time to Repair). For example, if an actual missile performance parameter deviates more than a certain percentage (e.g., 30%) from the desired value, the model

will delay both the development and the production schedule. A T&E-caused delay or revised procurement schedule may also be imposed on the model as a direct input.

A final element of R&D costs are those pilot production costs which are allocated to the R&D budget. These are taken from the Procurement sector; they include both recurring costs and the nonrecurring cost elements of initial tooling and test equipment, support hardware, data, and support engineering and program management. In the base case described in Chapter III, one-third of the pilot models are used for OPEVAL testing, so one-third of the recurring pilot costs are allocated to RDT&E. All of the initial tooling costs (since they are incurred before full production is under way), and one-half of the other nonrecurring pilot costs are also allocated to RDT&E.

The major outputs of the RDT&E sector are listed in Table 2-2. These include both the RDT&E cost components which are calculated by the RDT&E sector, and the share of pilot production costs which are allocated to the RD& budget. The RDT&E sector also provides timing inputs to the Procurement sector, and thus, indirectly, to the O&S sector. The timing of these later phases of the program life cycle is determined by the RDT&E sector of the model.

TABLE 2-2. RDT&E Sector Outputs

RDT&E Completion Times

Delays in Procurement

RDT&E Costs & Spending Profile

- Missile RDT&E Costs
  - Nonrecurring Prototype
  - Recurring Prototype
  - Support Equipment
  - Data
  - Testing & Evaluation
  - Systems Engineering/Program Management
- Allocated Pilot Production Costs
  - Recurring
  - Nonrecurring
    - Initial Tooling & Test Equipment
    - Support Hardware
    - Data
    - Support Engineering/Program Management

The next section describes the Procurement sector of the cost-estimating model.

2.4. PROCUREMENT SECTOR

2.4.1. Overview

The Procurement sector is concerned with the total costs and time-pattern of spending for procurement of the missile. Figure 2-3 provides an overview of this sector of the model.

Based on the inputs provided, the Procurement sector calculates the base case, constant-dollar recurring costs of missile procurement. The estimated average unit cost of the first 1000 missiles is provided to the RDT&E sector as an input to the RDT&E cost calculations.

The procurement schedule as specified by the model input is modified to take into account any T&E delays passed on by the RDT&E sector of the model. The number of missiles procurred and the finalized delivery schedule are important inputs to the O&S sector of the model. Recurring procurement expenditures are then distributed in a pattern of spending over the time span of procurement.

Nonrecurring procurement costs are calculated by CER's supplied by OP-96D for the major categories of initial tooling, support hardware, spares, and aggregate support. These costs are also distributed in a spending profile over the procurement schedule.

Pilot production costs, both recurring and nonrecurring, are calculated just like the other production costs but are tracked separately by the Procurement sector. The pilot production costs are passed to the RDT&E sector, which then allocates specified portions of the costs to the RDT&E and to the procurement budget categories.

The format of the model's procurement cost outputs is shown in Table 2-3:

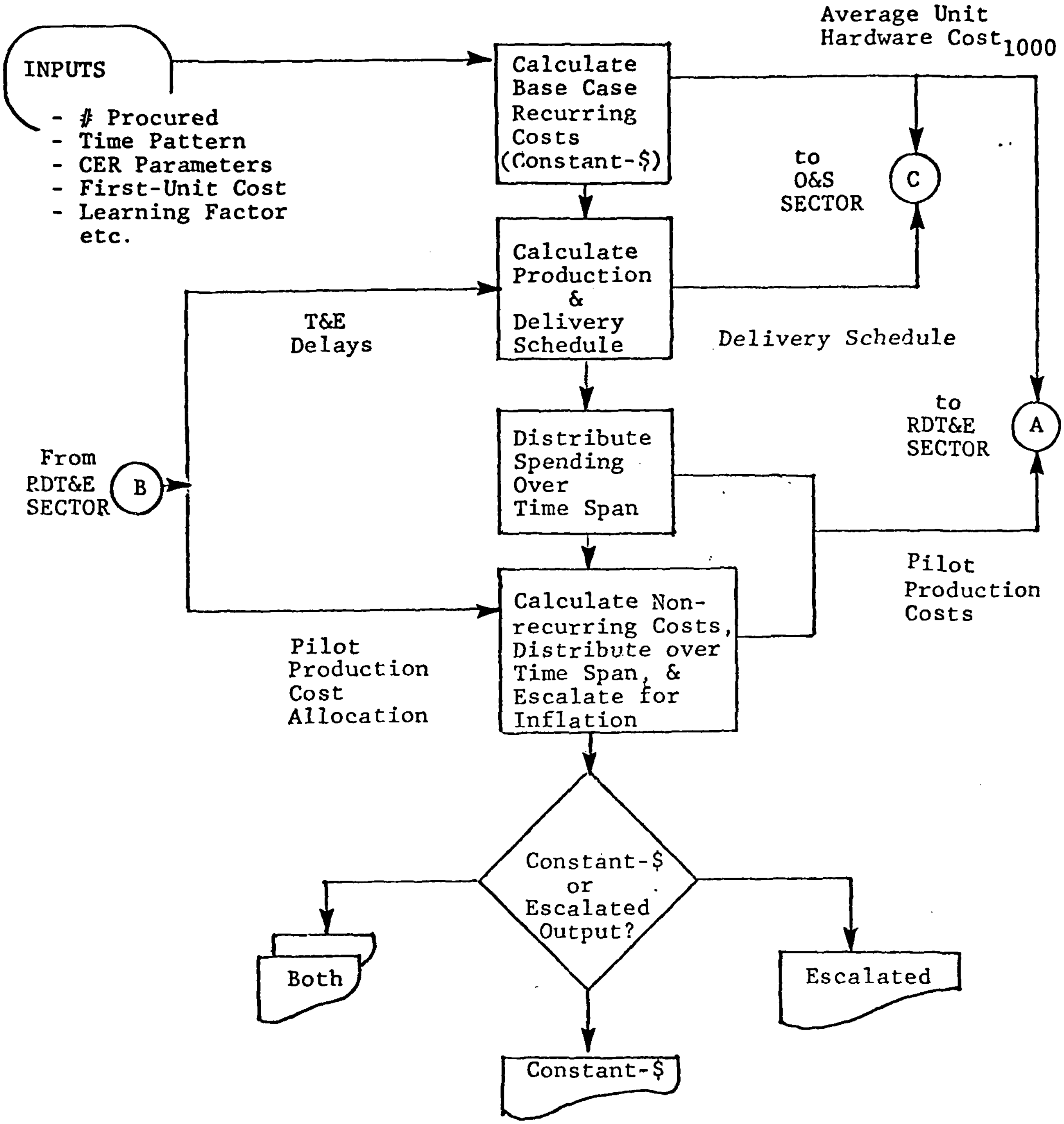

FIGURE 2.3 Procurement Sector Overview

TABLE 2-3. Procurement Sector Outputs

Production & Delivery Schedule

Average Unit Hardware Cost

Procurement Costs & Spending Profile

- Recurring Procurement
  - Fixed / Direct
  - Variable / Indirect
- Nonrecurring Procurement
  - Initial Tooling & Test Equipment
  - Support Hardware
  - Spares
  - Aggregate Support
    - Support Engineering/Program Management
    - Follow-On OT&E
    - Training Services & Equipment
    - Data
    - ECP'S/ECO'S
- Allocated Pilot Production
  - Recurring
  - Nonrecurring
    - Initial Tooling & Test Equipment
    - Support Hardware
    - Data
    - Support Engineering/Program Management

The recurring, nonrecurring, and pilot production cost estimation procedures are described in the following subsections.

2.4.2. Recurring Procurement Costs

The Procurement sector incorporates a representation of the recurring procurement cost model developed for OP-96D by Wilbourn and Linder.* This model builds upon the frequently-used cost-improvement-curve cost-estimating approach, but it is considerably more detailed than the simple cost-improvement-curve technique. It takes into consideration both fixed and

*"The Effect of Production Rate on Recurring Missile Cost: A Theoretical Model", OP-96D Working Paper.

variable direct and overhead costs, including the effect of the other business base of the missile contractor and the rate of production, as well as the effect of the cost-improvement curve. An outline of the mathematical formulation of this model is presented in Table A-2 in Appendix A.

The model calculates costs based on a specified procurement schedule. The programmed number of missiles to be procured each year is an input to the recurring production cost model. Depending on the status of RDT&E, procurement may be delayed. If this occurs, the entire procurement schedule is slipped by the model for the length of this time period. The model then estimates the cost of each year's production, based on such cost inputs as fixed overhead costs, the other business base of the contractor, the variable overhead rate, fixed direct costs, unit costs not subject to learning, first-unit cost, and the slope of the cost-improvement curve. In order to minimize fluctuations in the labor force, the contractor will desire to expend these costs at a nearly constant rate over the year. But because of the cost-improvement curve, unit costs will decline as more and more missiles are produced. Thus, the production and delivery rate will rise over the course of each year, due to the cost-improvement curve's effect of reducing direct costs per missile. While this is occurring, the model totals up the direct and overhead costs incurred.

The recurring production cost model can actually be operated with just a few of the cost inputs described. This use will provide less-detailed cost estimates, but may be necessary depending upon the actual level of input cost data available.

2.4.3. Nonrecurring Procurement Costs

The Procurement sector includes a number of statistically-derived CER's which were provided by OP-96D for use in analysis of all air-launched missile programs. These are used to generate the estimates for each of the nonrecurring procurement cost elements listed in Table 2-3, Procurement Sector Outputs. The formulation of the ten CER's is described in Table A-3 in Appendix A. The model distributes the total cost for each component over a time-pattern of spending. Inputs to the nonrecurring procurement CER's include the total number of missiles to be procured, the peak production rate, total recurring hardware costs, and the average unit hardware cost of the first 1000 missiles. In using the model to make cost estimates, the number of missiles to be procured and the peak production rate are supplied as inputs by the analyst. Total recurring hardware costs and the average unit cost of a 1000-unit lot are calculated endogenously by the recurring procurement cost model described above.

2.4.4. Pilot Production Costs

Pilot production costs are calculated in the same manner as full-scale production costs. Both recurring and nonrecurring costs are estimated, and the nonrecurring cost elements include initial tooling, support hardware, support engineering and program management, and data costs. These costs may be allocated between the procurement budget category and the RDT&E category. The mechanics of this allocation were previously described in the section on the RDT&E sector.

The next section describes the O&S sector of the cost-estimating model, and the calculation of O&S cost and readiness estimates.

2.5. O&S SECTOR

2.5.1. Introduction

The O&S sector estimates the direct O&S costs, broken down by budget category, of operating and supporting a Navy air-launched missile system. The O&S sector does this by simulating the many activities involved in missile operations and support and adding up the costs associated with those activities over the service lifetime. Section 2.5.2 describes the major O&S activities, flows, and inventories of missiles which are represented by the O&S sector and the O&S cost calculations performed, including the major inputs and outputs of the sector. Finally, the measures of missile hardware readiness calculated by the O&S sector are described in Section 2.5.3.

2.5.2. O&S Activities and Cost Calculation

The O&S sector of the cost-estimating model is a system dynamics simulation model of the major activities involved in missile operations and maintenance. An overview of these activities is depicted in Figure 2-4. These activities, flows, and inventories of missiles are all represented in the O&S model.

As the O&S sector simulates the activities and flows of missiles, calculations are performed which generate the O&S cost estimates. An overview of the sector's simulation and cost calculations is presented in Figure 2-5. The major inputs to the sector, its calculations, and its major outputs are described below.

The major inputs to the O&S model are of four basic types. These are

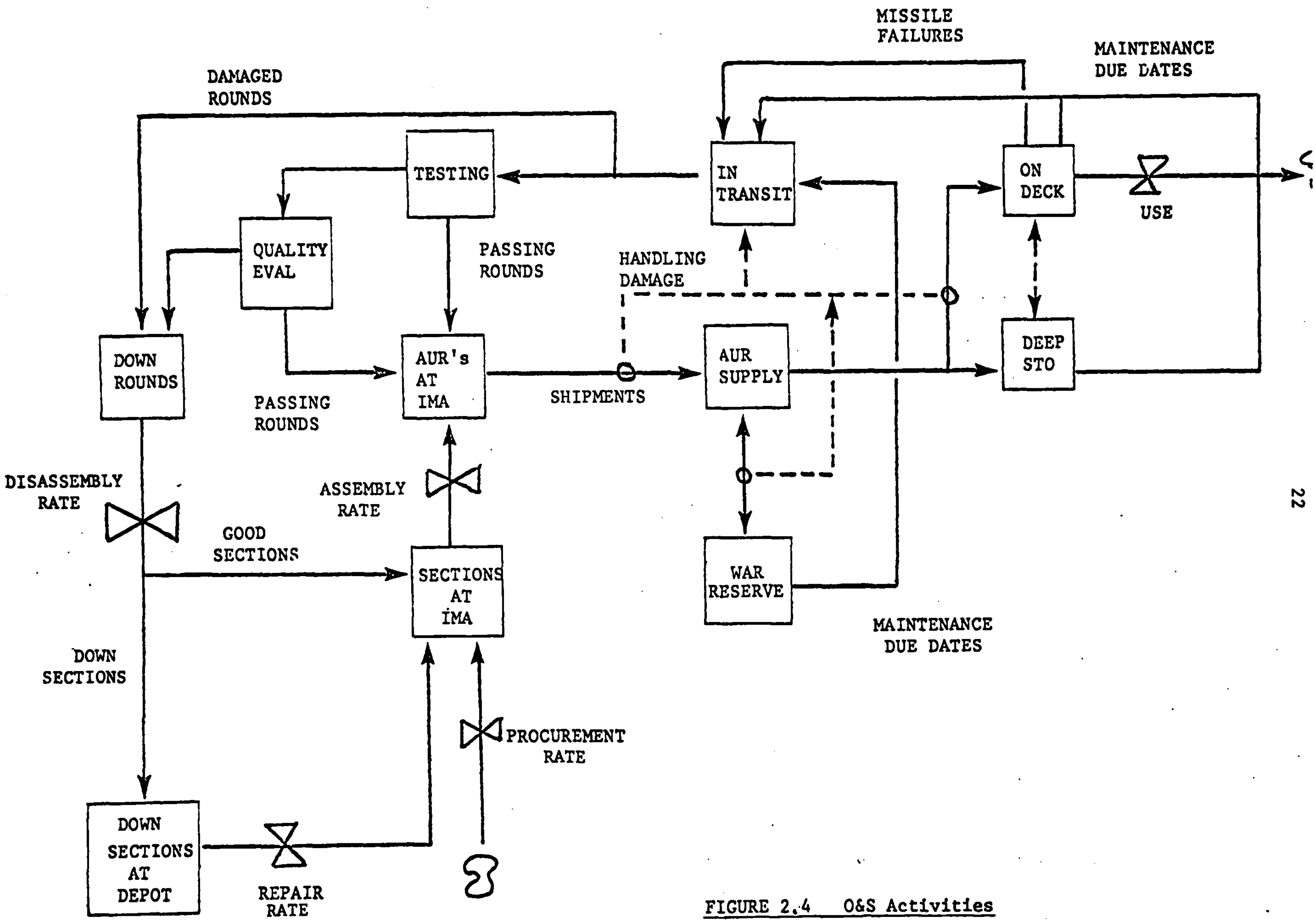

FIGURE 2.4 O&S Activities

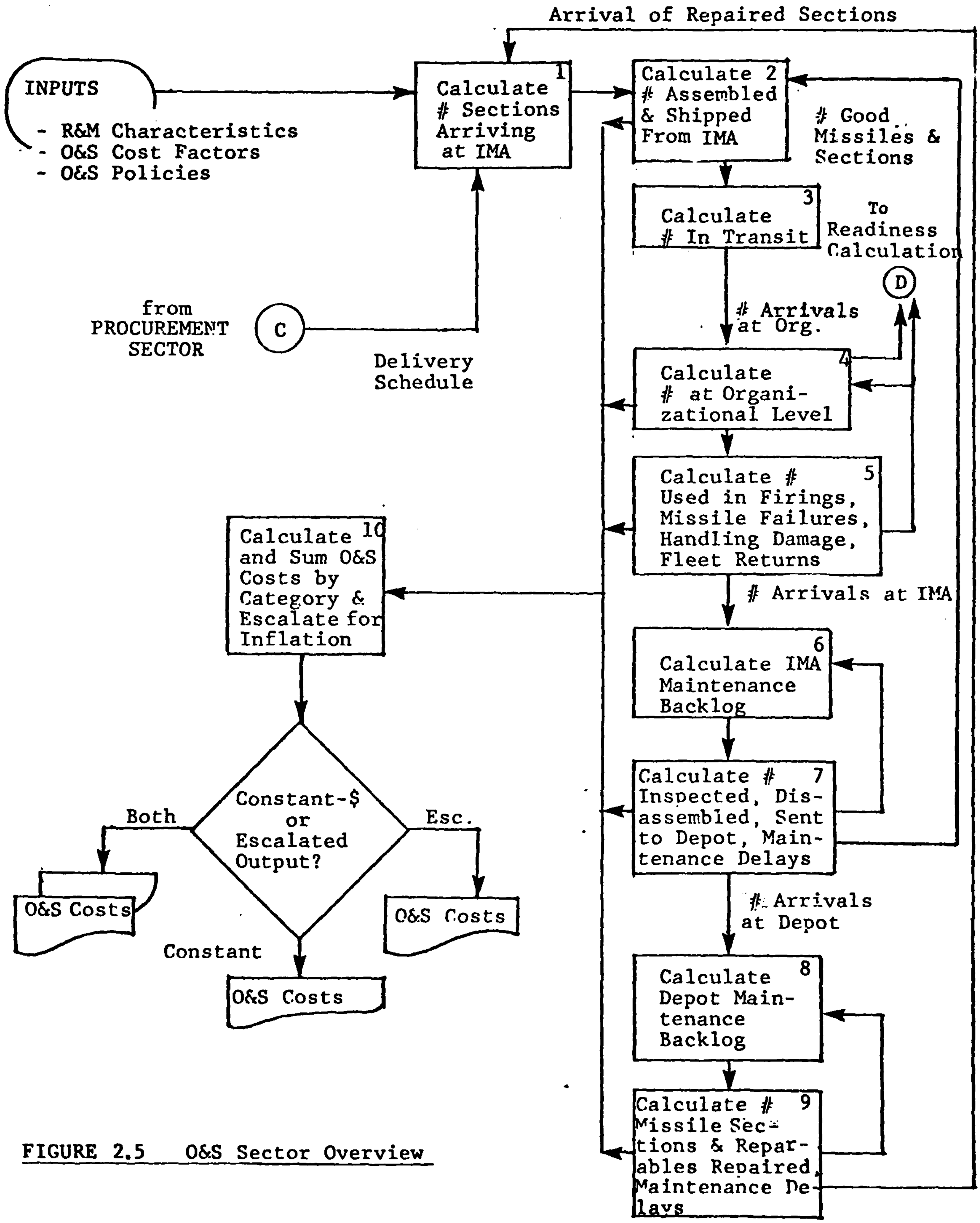

FIGURE 2.5 O&S Sector Overview

the procurement inputs, the missile reliability and maintainability characteristics, O&S cost factors, and O&S policies. The major procurement input is the number of missiles which are procured and which have to be supported. This number is calculated by the Procurement sector, as it simulates the delivery of missiles to the O&S sector. Reliability and maintainability inputs include parameters such as the mean time between failures (MTBF, or average failure rate), the missile's rate of decay while on the shelf, its susceptibility to handling damage, and its mean time to repair (MTTR, measured in manhours). Cost factor inputs include the cost per manhour of maintenance, maintenance facility overhead rates, and the cost per ton-mile of shipping. Finally, O&S policies are also specified as inputs. These include the interval between maintenance due dates, "fly-until-die" versus "rotation" of captive-carry training missiles at the organizational level, desired inventory levels, and reparables, and consumables supply policies. A detailed list of these inputs, together with their base case values, can be found in Table 3-1 in Section 3.1. These inputs can easily be varied to perform estimates of O&S costs for many different alternative cases, as illustrated in the later sections of Chapter III.

Figure 2-5 indicates the sequence of computation within the O&S sector. It should be noted that this entire sequence of calculations is performed at each time step in the simulation. Rates are calculated, inventories and backlogs are updated, and rates are recalculated based on the updated states. In this manner, the model simulates the changing inventories, the shipment of missiles and missile sections, and the activities of the O&S system. (Numbers in parentheses in the text refer to the boxes in Figure 2-5). These calculations begin with computation of the number of missile sections arriving at the IMA (1) based on the delivery schedule received

from the Procurement sector. Missile assembly and shipment rates from the IMA are then calculated (2). After a shipping delay (3), the missiles arrive at the organizational level and add to its inventory of all-up rounds.

The O&S sector keeps track of two distinct groups of missiles at the organizational level. One group, much the smaller, is kept "on deck", ready for use and employed in captive-carry training. The larger group is kept in deep storage. Current Navy policy for most missiles is that when an "on deck" missile fails, it is replaced from deep storage, but there is otherwise no rotation between the two groups. In the base case, the model simulates the segragation of these groups, although it can, if desired, simulate a "rotation" policy.

The organizational level inventory of missiles is decreased (5) by the number of missiles used in firings for operational training, the number of indicated missile failures, the number damaged in handling, and the number of fleet returns (rounds which have reached their maintenance due dates, the intervals of time between periodic maintenance inspections). These calculations are based upon the model inputs describing the missile R&M (reliability and maintainability) characteristics and the relevant O&S policies.

At this point, the O&S sector also calculates several measures of missile readiness, based upon the number of missiles available and their R&M characteristics. These calculations are described in Section 2.5.4.

The "failed," damaged, and returned missiles add to the maintenance backlog at the IMA (6). The O&S sector then calculates the inspection and testing rate at the IMA (7), which reduces the IMA maintenance backlog. Most rounds pass these tests, depending on the inherent reliability of the missile, the rate at which it degrades "on the shelf", and the accuracy of the built-in test (BIT) or aircraft avionics indicators. The number of missiles pass-

ing inspection are then made available for the calculation of the shipment rate back to the organizational level (2).

The rounds failing these tests, however, are not invariably "down" missiles, for the IMA and other test equipment is not perfect. The failing rounds, together with a small fraction of the passing rounds, are subjected to more extensive testing in the Quality Evaluation Center. The model calculates the number of missiles which fail here, and then the disassembly rate of the failed damaged missiles into their component sections (7). The number of good missile sections is made available for the calculation of the assembly rate into complete rounds at the IMA (2).

The O&S sector then calculates the number of missile sections and reparable parts which are repaired at the depot facility (9). This repair rate reduces the depot maintenance backlog. The maintenance delays involved in depot repair (and in IMA *maintenance* (7)) are calculated by the model based on inputs regarding the availability of consumable materials and reparable parts. The O&S sector assumes that sufficient labor is available at the maintenance facilities so as not to impose any additional delays. The final link in the simulation of O&S activities is the calculation of the number of repaired missile sections shipped back to the IMA (1) from the depot (9).

While the O&S sector is performing this simulation of O&S activities, calculations are performed which generate the O&S cost estimates (10). The individual O&S cost elements are allocated to the budget categories of military personnel (MPN), operations and maintenance (O&MN), and weapons procurement (WPN). Table 2-4 lists the O&S cost elements estimated by the model, together with an indication of their budget categories.

TABLE 2-4. O&S COST ELEMENTS

Cost Element	MPN	O&MN	WPN
	Budget Appropriation		
Handling and Inspection	x		
Operational Training	x	x	
Intermediate Maintenance	x	x	
Depot Maintenance	x	x	
Supply Support		x	
Quality Evaluation		x	
Second Destination Transportation		x	
Receipt, Segregation, Storage, and Issues (RSSI)		x	
Replacement Training	x	x	
Replenishment Spares			x

A brief description of each cost element and the method by which it is calculated follows below. In connection with these descriptions, Figure 2-6 superimposes the points in the missile O&S system at which these costs are incurred onto the diagram which illustrates O&S activities. This diagram illustrates the inventories, shipments, and activities contained within O&S simulation model. The mathematical equations used to calculate the O&S cost estimates are listed in Table 4-A in Appendix A.

Handling and Inspection costs are for the personnel needed to perform all of the tasks involved in the unit operation of missiles, at the organizational level. These costs are determined by the number of men devoted to missile handling and inspection and the cost per man year, and they are allocated to the military personnel category, MPN.

Operational Training covers the cost of operational missile firings, including range costs, targets, and so forth.. These costs depend on the number of training firings per year and the cost per firing. This training

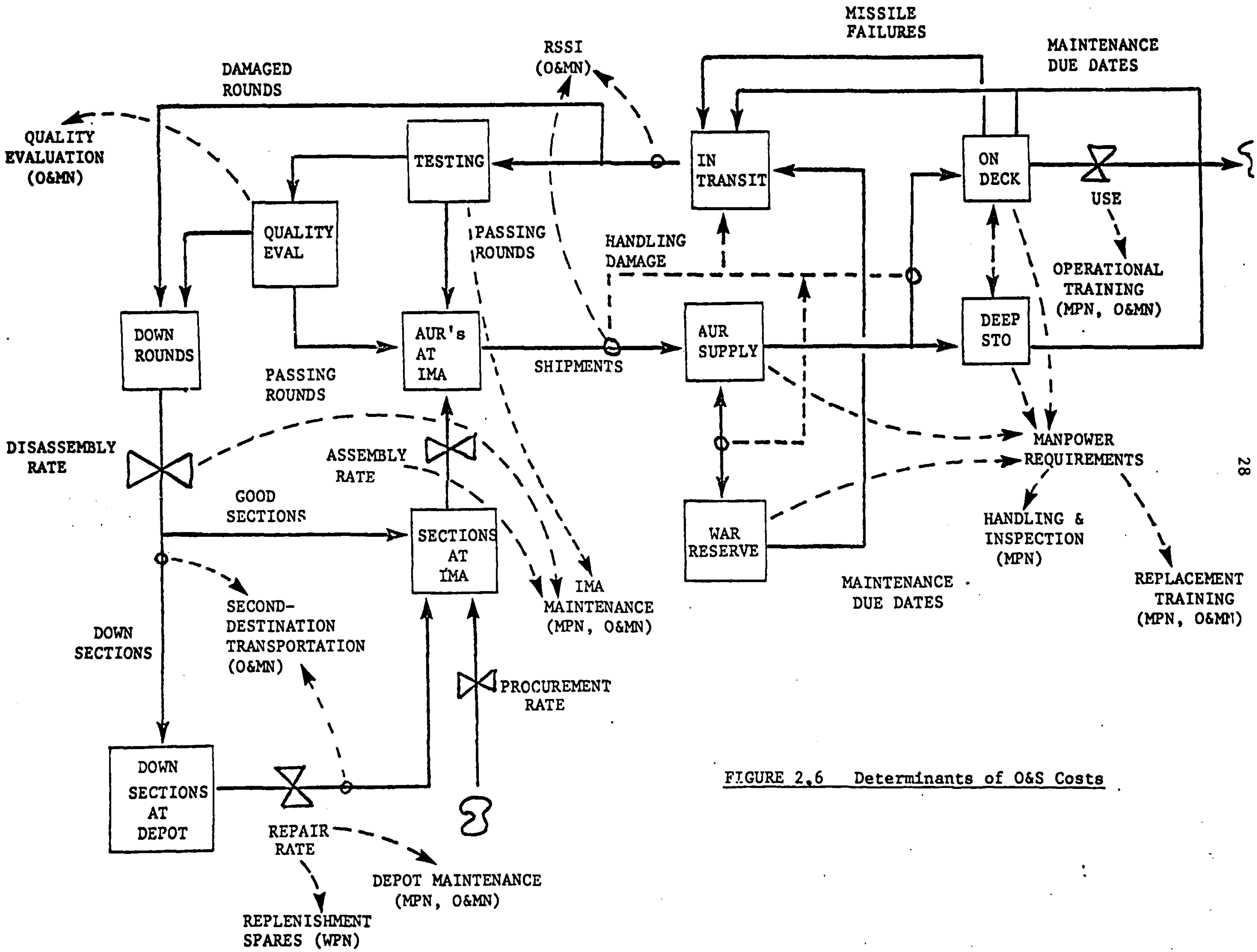

FIGURE 2.6 Determinants of O&S Costs

is allocated to the budget categories of MPN and O&MN, Operations and Maintenance.

Intermediate Maintenance covers the cost of personnel, consumable material, and overhead needed for missile checkout and repair at Naval Weapons Stations and Mobile Missile Maintenance Units. Each activity performed at the IMA (testing, disassembly, and assembly) requires a specified number of manhours and amount of consumables per missile. Some of the labor may be performed by military personnel; this cost is allocated to MPN. The other costs, including the IMA overhead rate as a percentage of labor costs, are allocated to O&MN.

Depot Maintenance costs include manpower, consumable material, and overhead needed to perform missile and component maintenance, including the repair of reparables, at NARF's, contractor repair facilities, and other depot overhaul points. The number of repairs, the number of manhours required per repair, and the cost per manhour determine the labor cost element of depot maintenance costs. Each repair also requires a certain amount of consumable supplies. Together with the depot overhead rate, these costs are allocated to the MPN and O&MN categories.

Supply Support covers the costs of purchasing, storing, managing, and distributing supplies, spares, and repair parts. These costs are calculated as a percentage of the value of reparables and consumables used in maintenance activities, and are included in O&MN.

Quality Evaluation includes the cost of testing of missile components and test equipment, certification of failures, and related activities. This is largely performed at the IMA, but it is a separate cost element. The costs of quality evaluation are calculated like those of IMA maintenance,

based on labor requirements, consumables usage, and an overhead rate. They are included in the O&MN budget category.

Second Destination Transportation costs are incurred in transporting the missiles or missile sections from the intermediate to the depot repair facilities. These costs depend on the number of sections shipped, their average containerized weight, the distance shipped, and the cost per ton-mile. Allocation is to O&MN.

Receipt, Segregation, Storage and Issues (RSSI) costs arise from the on-loadings and off-loadings of ships, and movement and handling of missiles to and from storage depots and weapons stations. These costs, included in O&MN, are determined by the number of rounds being processed, their containerized weight, and the cost per ton.

Replacement Training covers the costs of training personnel, their pay and the costs of their instruction. This is primarily for handling personnel, but a pro-rata share of training aircraft weapons system crew may also be included. The number of personnel, their average turnover times and pay rates, and other training costs per man determine replacement training costs. These are allocated to MPN and to O&MN.

Replenishment Spares includes the cost of buying the missile system spares, excluding initial spares procurement. This is for the acquisition of spare parts to replace those reparables which are not economically repairable. These costs depend on the number of reparables needed and their average cost per unit. They are allocated to weapons procurement, WPN.

All of these costs are calculated at each time interval as a current rate of spending, and then accumulated by budget category, so that either current expenditures or the cumulative total cost can be output. A number of O&S cost

elements are not included in the model in its current state. These include base operating support, fleet support, contractor technical services, in-service engineering, other technical support, modifications, and replenishment of support equipment. These costs are not included because they are of a less direct nature, and/or because they are less intimately related to the basic flow of O&S activities.

In addition to the cost estimates, several measures of missile hardware readiness levels are also estimated by the O&S sector. These are described in the next section.

2.5.4. Readiness Calculation

Readiness estimates are calculated in the model to provide a more accurate picture of the "services" provided, in terms of missile readiness, at the cost of a particular level of expenditures. This overall picture of life-cycle costs versus readiness is essential in comparing alternative cases. A missile with low reliability and maintainability will generate both high O&S costs and low readiness levels. But on the other hand, a higher level of spending (for example, to obtain a better design, or on preventive maintenance) may raise readiness levels. In addition, readiness, like missile O&S costs, depends on the interactions between the inherent reliability and maintainability characteristics of the missile and the policies which guide O&S activities.

Several simple measures of readiness are calculated within the O&S sector to provide means for comparing alternative cases and potential trade-offs of this type. These readiness measures are based on the number of missiles which are available for operations and on their reliability characteristics. The readiness measures are listed, with summary descriptions, in Table 2-5. The structure of readiness calculations are shown in Figure 2-7.

TABLE 2-5. Readiness Measures

- **NUMERICAL READINESS**

  Number of all-up rounds (AUR's) available for operations, not undergoing maintenance or in transit to maintenance facilities

- **PERCENTAGE READINESS**

  $$= \frac{\text{"Ready" AUR's}}{\text{Rounds in System}}$$

  Rounds in system include the rounds and missile sections undergoing maintenance and in transit to maintenance facilities

- **LIKELY READINESS**

  $$= \text{Numerical Readiness} \times \text{Likelihood of Successful Checkout}$$

  $$\text{Likelihood of Successful Checkout} = (1 - \text{Handling Damage Rate}) \times (1 - \text{Shelf Life Failure Rate}) \times (1 - \text{Aircraft Avionics/BIT "No-Go" Indication Rate})$$

- **PERCENTAGE LIKELY READINESS**

  $$= \frac{\text{"Likely Ready" AUR's}}{\text{Rounds in System}}$$

- **TOTAL LIFE-CYCLE HARDWARE READINESS**

  Cumulative number of AUR's "Likely to be Ready" over program life cycle

  Dimensions of "Ready Missile-Years"

  1 AUR x 1 Year = 1 Missile-Year

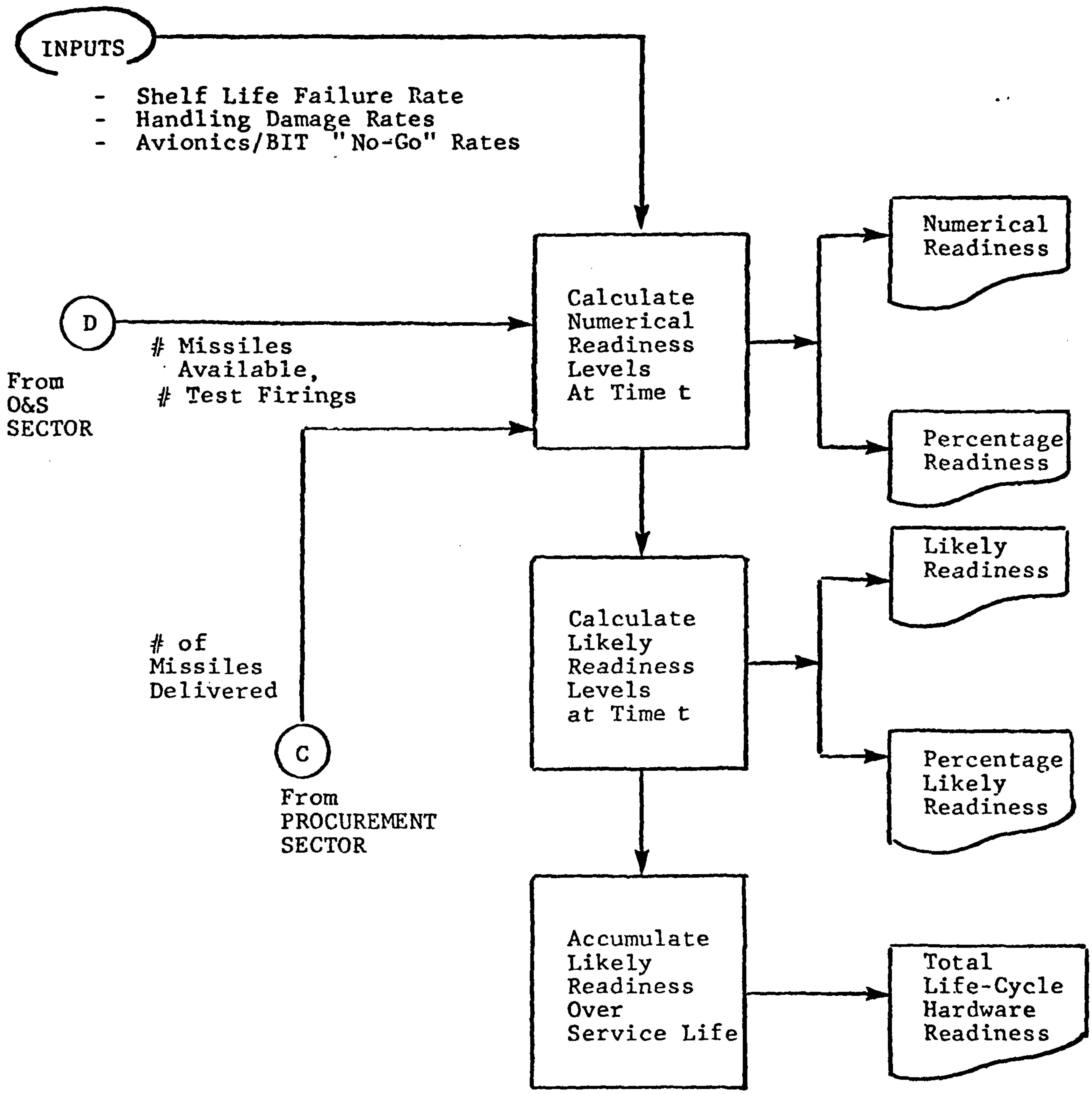

FIGURE 2.7 Readiness Calculation

The first, simplest measure of readiness is simply the number of all-up rounds which are available to the fleet. This is the same as the number of missiles which are not undergoing maintenance or in transit to or from the fleet. So, this measure simply indicates the availability of missiles for operations. This measure is called the "numerical readiness" provided by the missile program at a specific point in time.

A related measure is the fraction of missiles in the O&S system which are available to the fleet relative to the total number of missiles. This "percentage readiness" discounts the impact of simply procuring more missiles to increase the number available. A missile which requires more frequent and more time-consuming maintenance will, other things held equal, have a lower percentage readiness by this definition, no matter what the number procured.

A truly accurate picture of missile hardware readiness, however, is not reflected by a simple enumeration of the number of missiles available to the fleet. If the missile's reliability is low, many of those available missiles will be useless. An "available" round may be damaged in handling, it may have failed while in storage, or aircraft avionics or its BIT may indicate a missile failure when it is readied for use. These factors are taken into account in calculating another definition of readiness, the number of all-up rounds "likely to be ready". For this measure, the numerical readiness is adjusted by the rates of handling damage, shelf-life failure, and aircraft avionics/BIT-indicated failure experienced. For example, if two percent of the missiles are damaged in handling before use, then the numerical readiness is adjusted downward by two percent in calculating the

"likely readiness". As before, one can also compare this number to the total number of rounds in the O&S system to obtain a measure of "percentage likely readiness". These "likely readiness" measures indicate not only the availability of missiles, but also the efficiency of the missile design and O&S system in providing ready missiles.

Finally, a measure of "total life-cycle hardware readiness" is desirable for comparison with total life-cycle costs. To obtain this measure, the number of all-up rounds likely to be ready is accumulated over the course of the missile program life cycle. Each missile which is likely to be ready for one year adds one missile-year to the total life-cycle hardware readiness level. It is this measure which is most appropriate in comparing readiness and life-cycle costs for alternative designs or support concepts.

These readiness measures are, of course, simply formulated. They do not take into account how the missile will perform in its intended combat role. The readiness estimates calculated by the O&S sector do, however, provide a means for comparing alternative costs according to specific readiness criteria. As more complete readiness measures are developed, they can be implemented within the model. These measures may, for example, separately track the availability and "likely readiness" of missiles aboard ships with the fleet and those in the war reserves magazines. Measures of aboard-ship readiness, in particular, could be significantly elaborated. For example, these might be based on the ship-full requirement and the ability of the O&S system to maintain this level.

The following brief section summarizes the linkages among the sectors of the cost-estimating model.

2.6 SECTOR LINKAGES

The three major sectors of the life-cycle-cost estimating technique are mutually interdependent. Although the sectors perform their calculation independently for the most part, the RDT&E and Procurement sectors provide inputs to the other sectors. These linkages are outlined in Table 2-6.

TABLE 2-6. Sector Linkages

from \ to	RDT&E	Procurement	O&S
RDT&E		initiation time	IOC (via procurement)
Procurement	unit hardware cost, pilot production costs		deployment rate, cost of spare parts

The RDT&E sector initiates the procurement phase at a time which depends on the length of any delays which may occur in TECHEVAL or OPEVAL. Thus, it indirectly sets off operations and support activities, which begin when the first missiles arrive from the Procurement sector. The calculated deployment of the missiles, which increases the level of O&S spending, is driven by the procurement rate determined by the Procurement sector.

The Procurement sector also supplies cost inputs to the other two sectors. In the O&S sector, the cost of spare parts depends on the unit hardware cost of the missile. The unit production cost is also an input to the cost-estimating relationships of the RDT&E sector. Finally, the procure-

ment sector estimates the costs of the pilot production lot, some of which may be allocated to the RDT&E budget.

The next chapter describes applications of the cost-estimating technique, including a benchmark base case forecast and alternative projections investigating an alternative maintenance concept, different reliability and maintainability characteristics, and delays occurring during T&E.

III. APPLICATIONS OF THE LIFE-CYCLE COST-ESTIMATING MODEL

This chapter illustrates a number of applications of the Navy air-launched missile life-cycle-cost-estimating model. It presents descriptions of the benchmark base case forecast and alternative projections investigating i) an alternative maintenance concept, ii) different reliability and maintainability characteristics, and iii) delays occurring during T&E. These example applications indicate cost implications, the breadth of analyses possible with the model, and the ease with which they can be undertaken. A number of sensitivity analyses have also been performed with the model and are described briefly.

These applications of the model begin with the base case projection and cost estimate described below. This projection is based upon a set of specific characteristics representative of an "average air-launched missile", and not upon any particular missile program. Thus, the cost estimates presented and the results of the analyses performed are illustrations of the types of analyses which can be done with the model, not forecasts or analyses of a specific program. Application to a specific program would require program specific input characteristics and possible modification and refinement of some cost equations.

All cost estimates presented in this chapter are given in terms of constant (FY77) dollars.

3.1. THE BASE CASE

The base case life-cycle-cost estimate described here has two major purposes. First, since all of the inputs to this estimate are intended to be representative of an average problem-free air-launched missile program, the base case projection will therefore be the model's "best estimate" for this

representative missile program. It represents the most likely cost of the missile program, assuming no major design, testing, or procurement scheduling problems. Second, the base case will provide a benchmark against which alternative case projections can be compared when conducting sensitivity and trade-off analyses.

The major inputs to the base case estimate are summarized below and in Table 3-2. The initial RDT&E program extends over a period of four years, with no delay in any phase. The pilot production lot numbers 120, and 40 of the pilot models are funded from the RDT&E budget. In full-scale production, 3000 missiles are procured over a period of five years. The recurring cost inputs are listed in Table 3-2; based on these inputs, the Procurement sector of the model will project an average unit recurring cost of about $71K (all costs are in constant, FY77 dollars).

A complete list of the inputs to the cost-estimating model, together with their base case values, is presented in Table 3-1. This entire list of inputs need not be provided to the model each time it is used. Only the inputs which differ from the base case supplied when an alternative projection is made. As the cases described below will illustrate, making most alternative projections will involve a simple change in just one or two of the major inputs.

Another group of inputs concerns missile O&S policy assumptions. After enough missiles have been deployed to fill up the pipeline, there are 40 training firings per year. Organizational units are assumed to follow a "fly-until-die" policy, that is, not rotating missiles between the small group kept ready for use and the larger group which is kept in deep storage. Every two years, the rounds at the organizational level are

TABLE 3-1. INPUTS TO THE LIFE-CYCLE COST MODEL

DEFINITION OF VARIABLE	VARIABLE TYPE*	VARIABLE NAME	BASE CASE VALUE
OVERALL MODEL			
Program Initiation Date	C	TIMEN	1975
4 Escalation Factors require 16 varied parameters (RDT&E, Procurement, MPN, O&MN Purchases)			
RDT&E SECTOR			
R&D Initiation Date	C	RDIT	1975
Planned R&D Time Span	C	PRDT	4 years
Number of Prototype Missiles	C	PON	40
Planned TECHEVAL Initiation Time,	C	PTEIT	year 2 (after program start)
Time Span	C	TET	1 year
TECHEVAL Delay	C	TEDAVC	0 years
Planned OPEVAL Initiation Time,	C	POEIT	year 3
Time Span	C	OET	1 year
OPEVAL Delay	C	OEDAVC	0 years
Number of Test Items for T&E	C	PNT	80
Fraction of T&E Costs in TECHEVAL	C	TEVF	0.7
6 RDT&E CER's require 20 constant parameters			
RDT&E Spending Time-Profiles require 8 parameters			
Missile characteristics (MTBF, etc.), to set off T&E Delays may employ up to 23 parameters			
Pilot Production Initiation Time	C	PP1lPT	year 3
Number of Pilot Models for RDT&E	C	RDPIN	40
R&D Fraction of Nonrecurring Pilot Production Costs:			
Initial Tooling	C	RDFPI	1.0
Support Equipment	C	RDFPS	0.5
Data	C	RDFPD	0.5
Program Management	C	RDFPM	0.5

*Variable Types: C Constant Parameter
T Table Function
(input is the y-axis values of a graphed relationship)

TABLE 3-1. INPUTS TO THE LIFE-CYCLE COST MODEL
(continued)

DEFINITION OF VARIABLE	VARIABLE TYPE	VARIABLE NAME	BASE CASE VALUE
Pilot Spending Time-Profiles require 15 parameters			
PROCUREMENT SECTOR			
Pilot Production Time Span	C	PIT	1 year
Number in Pilot Lot	C	PIN	120 missiles
Peak Pilot Production Rate	C	PKPIPR	150 per year
Pilot Spending Time-Profiles require 4 parameters			
Full-Scale Production Time Span	C	PRTT	5 years
Time to Produce First 1000 Units	C	TCAC	2.73 years
Peak Production Rate	C	PPR	815 per year
10 Nonrecurring Procurement CER's require 24 parameters			
Nonrecurring Spending Time-Profiles require 17 parameters			
Cost-Improvement Curve Slope	C	B	-0.1844
First-Unit Cost	C	FUNCC	84E3 (10^3) $
Nonlearning Cost Component	C	K4N	5E3 $
Fixed Direct Costs	C	K3N	288E3 $ per year
Variable Overhead Rate	C	K2N	0.5
Fixed Overhead Costs	C	K1N	27E6 $ per year
Other Business Base	C	OBBSN	12E6 $ per year
Change in Other Business Base	C	OBBS1	0
First-year (Pilot) Production Lot	C	NUM1T	120 missiles
Total Full-Scale Production Lot	C	NUMT	3000 missiles

TABLE 3-1. INPUTS TO THE LIFE-CYCLE COST MODEL

(continued)

DEFINITION OF VARIABLE	VARIABLE TYPE	VARIABLE NAME	BASE CASE VALUE
Fraction of Full-Scale Lot in			
Year 1	C	NUM1F	0
Year 2	C	NUM2F	0.12
Year 3	C	NUM3F	0.24
Year 4	C	NUM4F	0.26
Year 5	C	NUM5F	0.20
Year 6	C	NUM6F	0.18
Year 7	C	NUM7F	0
Fraction Cutback in Stretch-Out	C	PRVDV	0
Date of Initial Cutback	C	PRVDTT	2000
Time Span of Cutback	C	PRDEL	0 years
Initial Delivery Delay	C	PROCD	1 year
O&S SECTOR ACTIVITIES			
Desired Number of AUR's "On Deck" from 1980 to 1986, 2-year intervals	T	TDODOT	0/80/140/200 per year
Desired Number of Training Firings from 1980 to 1986, 2-year intervals	T	DUROT	0/16/28/40 per year
Desired Firings per Organizational Unit	C	DUROR	2 per year
Switch, 1 = "Rotation" Policy 0 = Fly Until Die	C	SWRO	0
Time "On Deck", when rotated	C	TODO	0.5 years
Tests per AUR "On Deck"	C	ATYO	2 per year
Normal Handling Damage Fraction	C	NHD	0.02 per move
Normal Indicated Missile Failure Rate	C	FRN	0.1 per BIT/ avionics test
Ratio of Indicated Missile Failures to Number of Actual Failures	C	MAFR	2
Shelf Life Failure Rate, "On Deck"	T	ASL1OT	
And Deep Storage	T	ASL2OT	
from 0 to 4 years, 0.5 year-intervals			0/.012/.025/.038/.05/.068/.074/.086/.098

TABLE 3-1. INPUTS TO THE LIFE-CYCLE COST MODEL

(continued)

DEFINITION OF VARIABLE	VARIABLE TYPE	VARIABLE NAME	BASE CASE VALUE
Shelf Life Failure Rate, in Reserve from 0 to 10 years, 1-year intervals	T	FSLRT	0/.021/.041/.061/.081/.1/.119/.137/.155/.173/.19
Maintenance Due Dates			
Organizational "On Deck"	C	MDODO	2 years
Organizational Deep Storage	C	MDDSO	2 years
Reserve Deep Storage	C	MDRES	5 years
Organizational Storage Capacity	C	CAPON	2000 missiles
Fraction Kept "On Deck"	C	ODOF	0.1
Shipment Capacity	C	CAPMN	1E6 missiles per year
Shipment Time, to Fleet	C	FWDTT	0.06 years
IMA Shipping & Handling Delay	C	IMAST	0.06 years
Inventory Coverage (Ratio of Stock to Use Rate), Missile Sections at IMA	C	AUSIT	0.06 years
Time to Test at IMA	C	IMATT	0.06 years
Time to Perform Quality Evaluation	C	IMAQT	0.06 years
Time to Disassemble at IMA	C	IMADT	0.06 years
Fraction of Missiles sent to IMA due to BIT/Avionics Indicators which Pass IMA Tests	C	TPFB	0.5
Fraction of Passing BIT/Avionics Missiles which are sent to Quality Evaluation	C	PBFQE	1.0
Ratio of Actual Missile Failures to Number of Indicated Failures among Fleet Returns	C	ATFR	0.5
Fraction of Passing Fleet Returns which are sent to Quality Evaluation	C	PSFQE	0.1
Labor Requirements per Missile at IMA			
Assembly	C	M1	16 manhours
Testing	C	M2	24 manhours
Quality Evaluation	C	MQ	24 manhours
Disassembly	C	M3	16 manhours

TABLE 3-1. INPUTS TO THE LIFE-CYCLE COST MODEL
(continued)

DEFINITION OF VARIABLE	VARIABLE TYPE	VARIABLE NAME	BASE CASE VALUE
Average Available Consumables Delay, IMA & Depot	C	AVDTI	0.06 years
	C	AVDTD	0.06 years
Fraction Consumables Available	C	CSAV	0.85
Unavailable Consumables Delay, IMA & Depot	C	CXDTI	0.25 years
	C	CXDTD	0.25 years
Shipment Time, to Depot	C	REARTT	0.06 years
Section and Repairables Repair Times, at Depot	C	SREPT	0.06 years
	C	PREPT	0.06 years
Inventory Coverage (Ratio of Stock to Use Rate), Reparables at Depot	C	PCOVT	0.06 years
Needed Reparables per Section	C	NPS	1
Fraction of Reparables Not Economically Repairable	C	FPX	0.2
Labor Requirements at Depot			
Section Repair	C	M4	40 manhours
Reparables Repair	C	M5	40 manhours
Available Reparables Delay	C	PACCT	0.06 years
Fraction Reparables Available	C	PSAV	0.85
Unavailable Reparables Delay	C	PXDTD	0.25 years
O&S COST FACTORS			
Cost per Enlisted Man	C	CPEM	10E3 $ per year
Cost per Officer	C	CPOF	20E3 $ per year
Handling Manpower per Unit	C	HMMNO	2 men
Manpower Turnover Time	C	HMMTO	2.5 years
Cost per Training Firing	C	CURUO	5E3 $
Fraction of Firing Costs to O&MN	C	FC20	0.8
Fraction of Military Personnel at IMA & Depot	C	MPFI	0.2
	C	MPFD	0

TABLE 3-1. INPUTS TO THE LIFE-CYCLE COST MODEL

(continued)

DEFINITION OF VARIABLE	VARIABLE TYPE	VARIABLE NAME	BASE CASE VALUE
Average Available Consumables Delay, IMA & Depot	C C	AVDTI AVDTD	0.06 years 0.06 years
Fraction Consumables Available	C	CSAV	0.85
Unavailable Consumables Delay, IMA & Depot	C C	CXDTI CXDTD	0.25 years 0.25 years
Shipment Time, to Depot	C	REARTT	0.06 years
Section and Repairables Repair Times, at Depot	C C	SREPT PREPT	0.06 years 0.06 years
Inventory Coverage (Ratio of Stock to Use Rate), Reparables at Depot	C	PCOVT	0.06 years
Needed Reparables per Section	C	NPS	1
Fraction of Reparables Not Economically Repairable	C	FPX	0.2
Labor Requirements at Depot			
Section Repair	C	M4	40 manhours
Reparables Repair	C	M5	40 manhours
Available Reparables Delay	C	PACCT	0.06 years
Fraction Reparables Available	C	PSAV	0.85
Unavailable Reparables Delay	C	PXDTD	0.25 years
O&S COST FACTORS			
Cost per Enlisted	C	CPEM	10E3 $ per year
Cost per Officer	C	CPOF	20E3 $ per year
Handling Manpower per Unit	C	HMMNO	2 men
Manpower Turnover Time	C	HMMTO	2.5 years
Cost per Training Firing	C	CURUO	5E3 $
Fraction of Firing Costs to O&MN	C	FC20	0.8
Fraction of Military Personnel at IMA & Depot	C C	MPFI MPFD	0.2 0

TABLE 3-1. INPUTS TO THE LIFE-CYCLE COST MODEL

(continued)

DEFINITION OF VARIABLE	VARIABLE TYPE	VARIABLE NAME	BASE CASE VALUE
Labor Cost at IMA	C	CPMH	12 $ per manhour
& Depot	C	CPSMH	16 $ per manhour
Overhead Rates at IMA	C	C4OR	1.25
& Depot	C	C6OR	1.5
Consumables Usage per Missile in:			
Assembly	C	CON1	50 $
Testing	C	CON2	50 $
Disassembly	C	CON3	50 $
Missile Section Repair	C	CON4	100 $
Reparables Repair	C	CON5	100 $
Fraction of Supply Support Costs, on	C	C7CR	0.15
Value of Consumables & Reparables	C	C7PR	0.15
Containerized Missile Weight	C	AVMWT	0.4 tons
Containerized Section Weight	C	AVSWT	0.12 tons
Transportation Costs	C	CPMILE	0.10 $ per ton-mile
Distance Shipped	C	AVRD	3000 miles
RSSI Costs	C	CPRND	74 $ per ton
Time to Train EM's	C	TTEM	0.28 years
Cost to Train EM's, Other than Pay	C	C16EM	2000 $
Number of Major Reparables per Missile	C	NPAUR	20

BASE CASE INPUTS

- 4-Year RDT&E program, with no delays
- 120 Pilot models, 40 allocated to RDT&E
- 3000 Full-scale production missiles, procured over a span of 5 years
- Recurring procurement cost elements:

First-unit direct costs	$ 84K
Other direct unit costs	$ 5K
Fixed overhead costs	$ 27M
Other business base	$ 12M
Variable overhead rate	50%
Fixed direct costs	$288K

- Operations and support policies:
  - 40 Training firings per year
  - "Fly-until-die", not "rotation", at organizational level
  - Maintenance Due Dates are every 2 years at organization, 5 years in reserve deep storage
  - 85% Reparables and consumables supply availability
- Reliability and maintainability parameters:

2% Handling damage rate
5% Rounds fail after 2 years at organization
10% Rounds fail after 5 years in reserve
10% Avionics/BIT "no-go" indication rate
40 Manhours to repair average "down" missile section

TABLE 3-2. Base Case Inputs

returned to the IMA for periodic inspection and maintenance. Missiles kept in deep storage in reserve magazines have a maintenance due date interval of five years. Reparable parts and consumable materials are assumed to be 85% available, that is, when needed for repairs, 85% will be obtainable within a few weeks. The other 15% are assumed to require an average of three months to obtain.

Finally, the reliability and maintainability parameters of the missile are listed at the end of Table 3-2. These characteristics of the missile design determine the workload imposed on the maintenance system by damaged and failed missiles.

When provided with these inputs, the model generates estimates of life-cycle costs, spending profiles, and readiness levels. The overall profile of the base case projected missile program spending is illustrated in Figure 3-1. The R&D program begins in 1975, and estimated R&D spending rises quickly to about $20 million per year by 1976. At the end of 1977, pilot production is begun. The large peak in spending at this time is caused by expenditures for initial tooling and test equipment. Full-scale production begins in 1979 and extends for five years, through 1983. During this period, procurement spending is calculated to be on the order of $40 to $70 million annually. Finally, as the missiles are deployed, estimated O&S spending begins to rise. As reflected in the model output shown in Figure 3.1, O&S spending for air-launched missiles is only a small fraction of total program spending.

The level of cumulative expenditures for the missile program is plotted in Figure 3.2. One can see that procurement costs account for the largest proportion of total life-cycle costs, while O&S costs, as for most Navy air-launched missile programs, are relatively small. Numerical estimates

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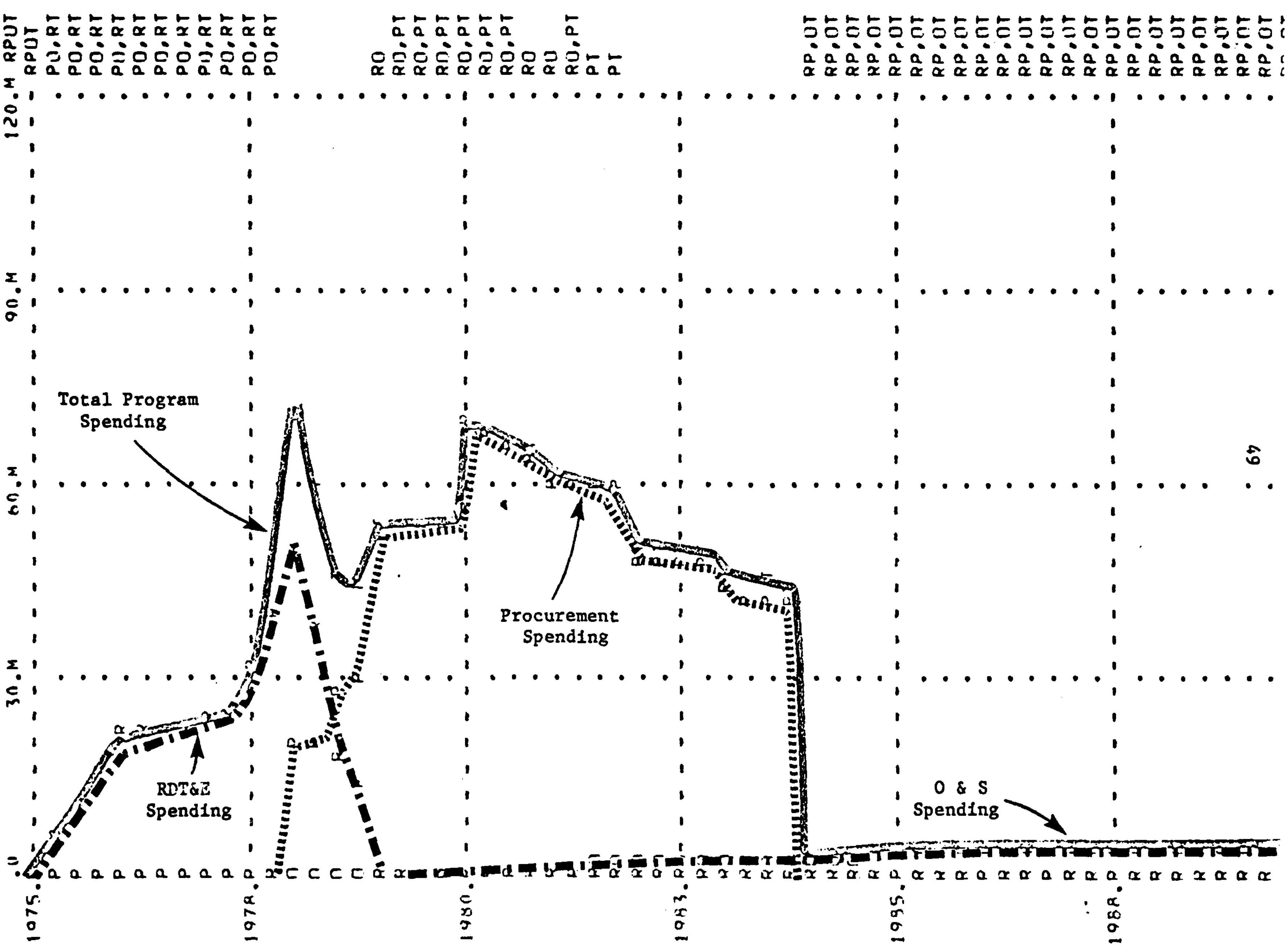

FIGURE 3.1 Spending Profile

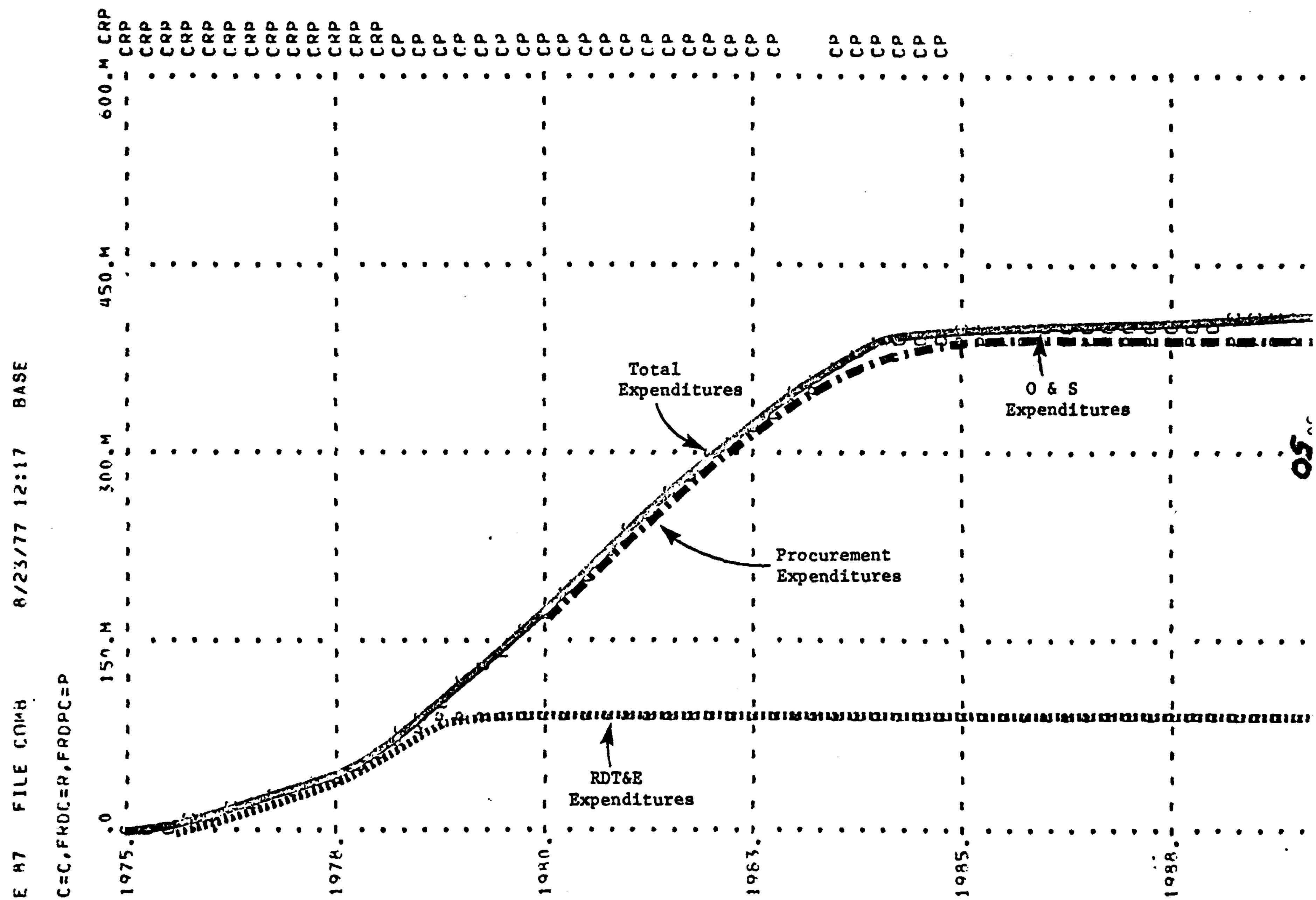

FIGURE 3.2 Cumulative Expenditures

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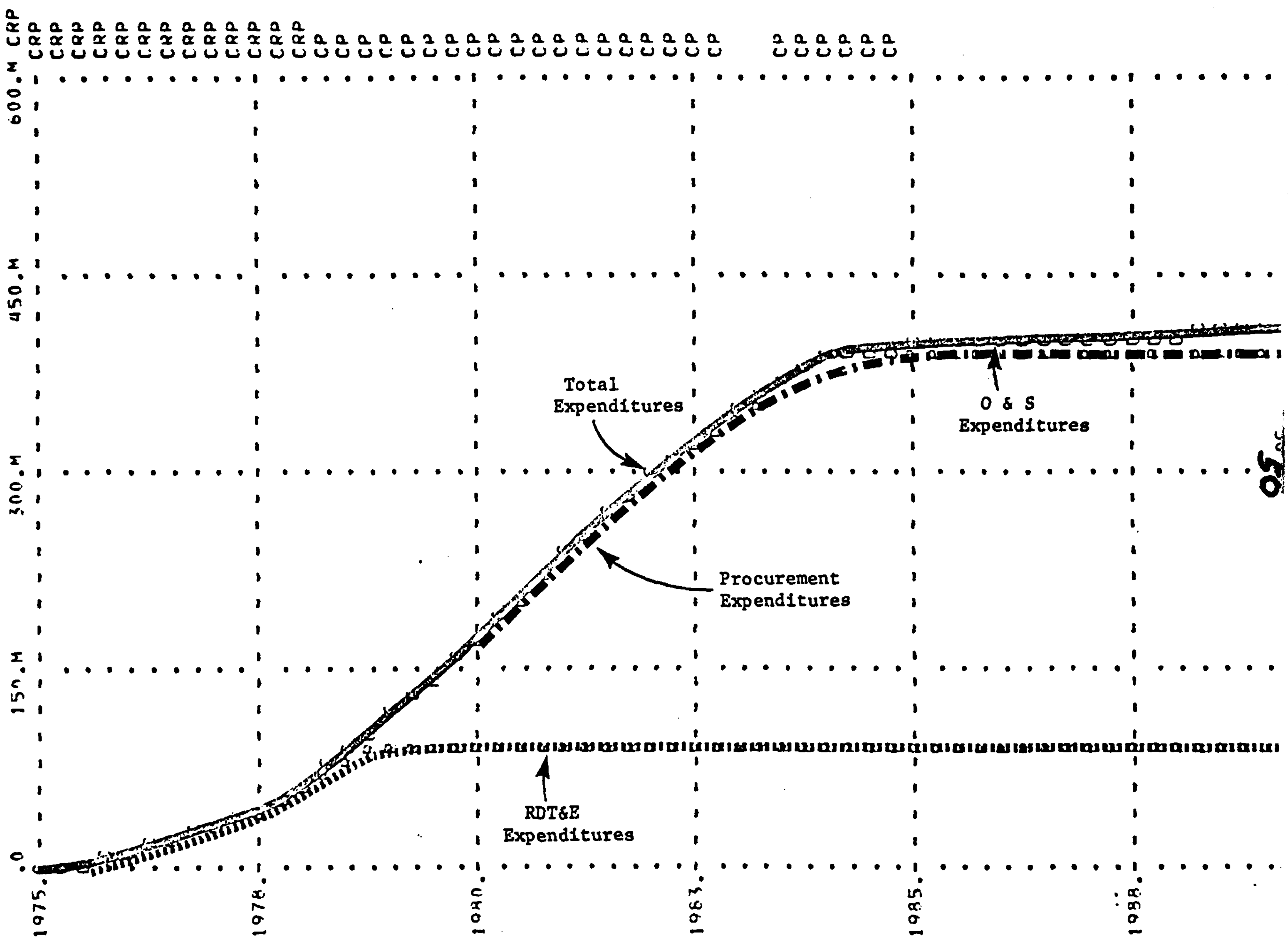

FIGURE 3.2 Cumulative Expenditures

of the major categories of life-cycle costs are presented in Table 3-3. The base case total life-cycle cost is estimated at $405.34 million, in 1977 dollars. RDT&E costs amount to $90.48 million, with the largest subcategories being nonrecurring prototype development costs and the R&D share of pilot production costs. Procurement costs are $290.09 million, about 70% of which are for the recurring costs. The cumulative average unit recurring cost, for all 3120 missiles, is estimated at $71,230. Finally, operating and support costs, through 1990, amount to $24.78 million. For this representative air-launched missile program, O&S costs account for approximately six percent of total life-cycle costs through 1990.

The annual rates of spending for direct missile operations and support are shown in Figure 3.3, and a detailed breakdown by cost element and budget category is tabulated in Table 3-4. Figure 3.3 illustrates the rise in O&S spending after the IOC in 1979 up to a little over $3 million per year by 1985. O&M expenditures are the largest component of O&S costs, followed by military personnel costs. WPN expenditures, for replenishment spares, are relatively small. Table 3-4 gives the numerical estimates for these annual O&S spending components for the representative year of 1990. Total direct O&S spending is about $3.2 million, with MPN about $1.2 million, O&MN about $1.9 million, and WPN a little over $0.1 million. The largest elements of the MPN category are handling and inspection and replacement training. These cost elements will not vary greatly when the "workload" on the maintenance system changes. But as the alternative projections described below will dramatically illustrate, the major components of the O&MN category are more variable. These cost elements (IMA and depot maintenance, and quality evaluation) are directly driven by the maintenance requirements of the missile system.

BASE CASE LIFE-CYCLE COSTS

Cumulative Cost Through 1990

Total Life-Cycle Cost ($M)	$405.34		
RDT&E		$90.48	
Non-Recurring Prototype			31.59
Recurring Prototype			2.43
Support Equipment			8.65
T&E			7.09
Data			2.69
Program Management			7.91
Pilot Costs			30.12
Procurement		$290.09	
Pilot Costs			15.33
Non-Recurring Production			70.53
Recurring Production			204.23
O&S		$24.78	
MPN			9.97
O&MN			13.73
WPN			1.08

TABLE 3-3. Base Case Life-Cycle Costs

BASE CASE ANNUAL O&S SPENDING

Annual O&S Costs (000 $77) in 1990		MPN	O&MN	WPN
Handling & Inspection		800		
Operational Training		40	160	
IMA		154	738	
Depot			552	
Supply Support			18	
Quality Evaluation			192	
Transportation			13	
RSSI			68	
Replacement Training		250	124	
Spares				128
Total	$3236	1243	1865	128

TABLE 3-4. Base Case Annual O&S Spending

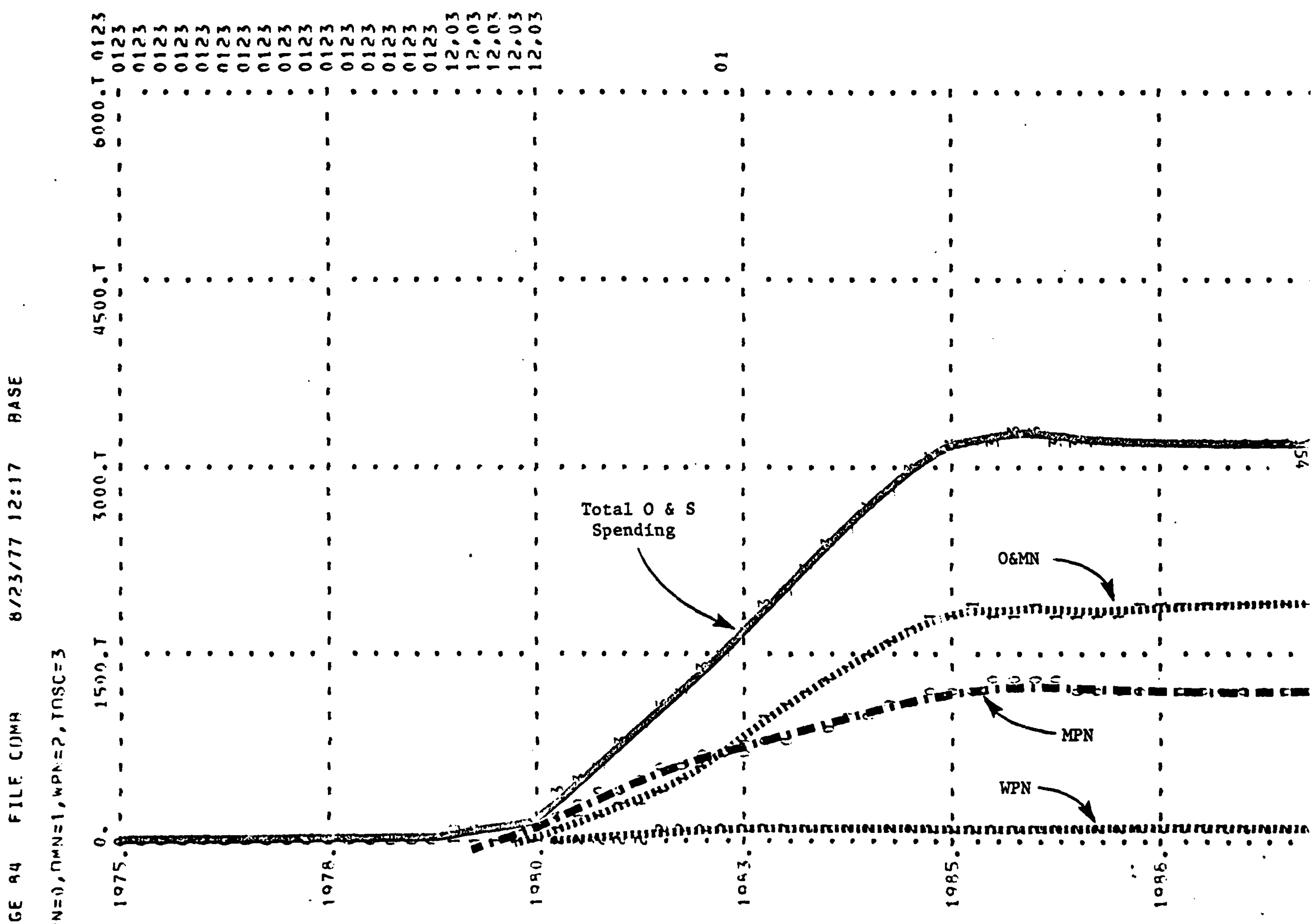

FIGURE 3.3 O & S Spending

In addition to the cost estimates, the level of readiness achieved will be important indicators for comparing alternative projections. The measures of readiness estimated by the model for the base case are shown in Table 3-5, and are illustrated in Figure 3.4

Over the life of the missile program through 1990, the base case projects 16,637 missile-years of total life-cycle hardware readiness. This is the cumulative number of all-up rounds "likely to be ready" over the time horizon. This is the measure most applicable for comparing alternative projections, because it is an estimate of readiness over the entire life cycle. The percentage likely readiness in the representative year 1990 is 75.6%. These two readiness measures are calculated based on the likelihood of successful missile checkout, allowing for the chances of handling damage, failure on the shelf, and so forth (as described in Chapter II). The percentage readiness, the adjusted fraction of rounds available for operations, is 91.6% in 1990. Figure 3.4 provides an illustration of the evolution of readiness over time. As more rounds are deployed, the number of missiles undergoing maintenance rises. After the initial "fill-up" period, however, readiness levels hold relatively steady.

Finally, Table 3.6 summarizes the major base case projections. The total life-cycle cost is $405.34 million, and the total life-cycle hardware readiness is 16,637. The estimates made with the model for alternative cases are described in the next sections of this chapter.

Total Life-Cycle Hardware Readiness	16,637
1990 Percentage Readiness	91.6%
1990 Percentage Likely Readiness	75.6%

TABLE 3-5. Base Case Readiness

Life-Cycle Hardware Readiness		16,637
Life-Cycle Cost ($M)		$405.34
RDT&E	90.48	
Procurement	290.09	
O&S	24.78	

TABLE 3-6. Base Case Summary

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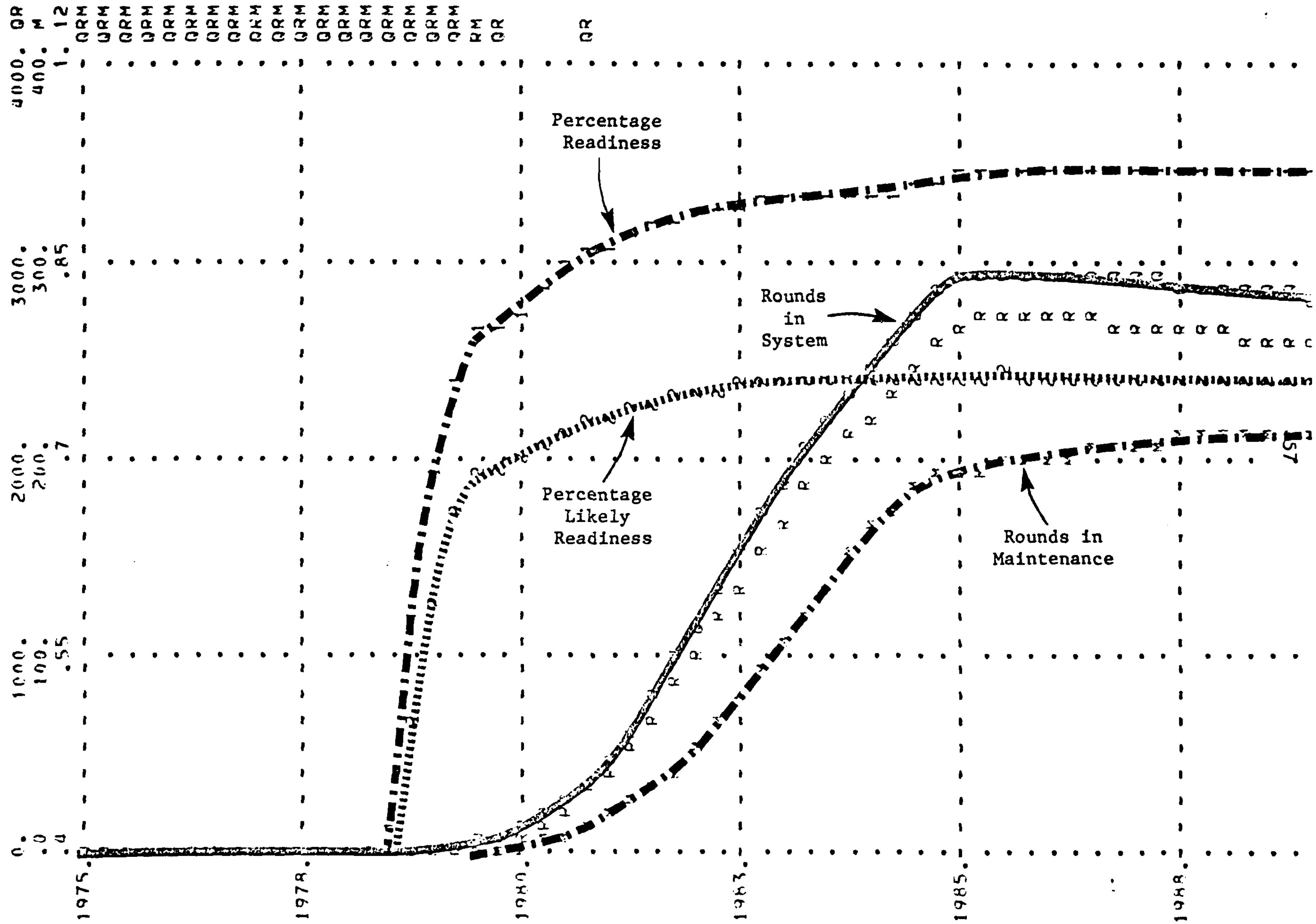

FIGURE 3.4 Readiness

3.2 ALTERNATIVE COST ESTIMATES AND TRADE-OFF ANALYSES

This section describes in detail three alternative projections made with the cost-estimating model. These projections investigate i) an alternative maintenance concept, annual maintenance due dates, ii) different reliability and maintainability characteristics, and iii) delays occurring during T&E and stretched-out procurement. These alternative cases are described in some detail to illustrate the ease with which the model can be used for various analyses.

3.2.1. Annual Maintenance Due Dates

The cost-estimating model can be used to demonstrate the impact of varying operations and support policies on life-cycle costs and readiness levels. Recently, within DoD, there has been some interest in attempting to increase readiness through more frequent maintenance. To investigate this issue, it is assumed for this projection that maintenance due date (MDD) intervals are reduced to one year for missiles at both the organizational level and in reserve deep storage. Every missile is returned to the IMA for periodic maintenance after one year, rather than after two or five years as in the base case. All other inputs remain the same as in the base case.

Because of the shorter periodic maintenance interval, the model calculates fewer missiles failing while in storage. On the other hand, the calculated maintenance system workload is increased greatly, since each missile is inspected more frequently. The O&S sector of the model, as it simulates missile O&S activities, estimates roughly twice as many fleet returns as in the base case, since the maintenance due date interval has been halved. For testing and inspection at the IMA, these fleet returns

consume double the labor manhours and consumable materials of the base case. A breakdown of O&S costs for this case and comparison with the base case are shown in Table 3-7. Total annual O&S spending in 1990 is up 32% over the base case projection. Spending for military personnel is little changed, but O&MN expenditures rise greatly. IMA maintenance and RSSI costs almost double from the base case, for it is at the IMA that the periodic inspection and maintenance is performed. Estimates for other cost elements are also increased, in part because the increased flow of missiles to and from the IMA raises the amount of transportation and handling damage incurred.

Besides raising O&S costs, the annual maintenance due date somewhat paradoxically lowers readiness levels, as indicated in Table 3-8. The lower readiness estimates result from the larger number of missiles which are calculated to be undergoing maintenance, or in transit to the IMA. Even though the missiles available for operations are more likely to be in a usable condition, having been inspected more recently than in the base case, there are simply fewer of them. Thus, the 1990 percentage readiness drops by six percentage points from the base case, while the percentage likely readiness (adjusted for the likelihood of successful missile checkout) drops by only two percentage points.

In summation, the annual maintenance due data policy raises life-cycle costs by about two percent, while lowering life-cycle readiness about three percent. This is tabulated in Table 3-9.

Annual O&S Costs ($000)

		MPN	O&MN	WPN	Base Case O&MN
Handling & Inspection		800			
Operational Training		40	160		160
IMA		222	1351		738
Depot			734		552
Supply Support			29		18
Quality Evaluation			251		192
Transportation			17		13
RSSI			130		68
Replacement Training		250	124		124
Spares				170	
Total	$4276	1311	2795	170	
Base Case	3236	1243	1865	128	

TABLE 3-7. Annual MDD O&S Spending

	Annual MDD	Base Case
Total Life-Cycle Hardware Readiness	16,064	16,637
1990 Percentage Readiness	85.4%	91.6%
1990 Percentage Likely Readiness	73.4%	75.6%

TABLE 3-8. Annual MDD Readiness Levels

				Change From Base
Life-Cycle Hardware Readiness		16,064		-3%
Life-Cycle Cost ($M)		$413.56		2%
RDT&E	90.48			
Procurement	290.09			
O&S	32.80		32%	

TABLE 3-9. Annual MDD Case Summary

These results, lower readiness with higher costs, may appear unusual. An annual maintenance due data policy will, however, improve readiness levels under certain conditions. The basic reason why readiness was impaired by going to an annual maintenance interval was that more "good" missiles were put into the maintenance pipeline than would have failed while sitting "on the shelf" in the base case. If the shelf-life performance of a missile is much worse than was assumed in the above projections, more frequent periodic inspection and maintenance would improve the readiness picture, at the cost of higher O&S expenditures. Results of this additional alternative case are shown in Table 3-10:

	Reduced Shelf Life With Annual MDD	Reduced Shelf Life With Base Case MDD
Life-Cycle Hardware Readiness	15,535	15,478
Life-Cycle Cost ($M)	$415.86	408.15
O&S	35.30	27.59

TABLE 3-10. Annual MDD With Reduced Shelf Life

The reduced shelf life projection is described in detail in Section 3.3.4.

3.2.2. Degraded Reliability and Maintainability

The cost-estimating model can also be used to examine the impact of different reliability and maintainability characteristics on life-cycle costs and readiness levels. For this projection, it is assumed that the missile is twice as "unreliable" as in the base case (failure rates are doubled: from 10% to 20% avionics/BIT "no-go" indications, from 2% to 4%

handling damage, and from 5% and 10% shelf-life failure rates to 10% and 20%). The maintenance requirements per missile processed are also increased. At the IMA, 25% more manhours are required for each missile assembled, tested, and/or disassembled, and at the depot level, manhour requirements are increased 50% (from 40 manhours to 60 per repair). All other inputs remain the same as in the base case.

Because of the missile's lower reliability, many more missile failures occur than in the base case projection. Since each maintenance operation requires more manhours of labor, the calculated workload on the maintenance system is increased greatly. A breakdown of O&S costs and comparison with the base case are shown in Table 3-11. Total annual O&S spending is up 65% over the base case projection. Depot maintenance costs, in particular, increase dramatically, to more than three times the base case level. Roughly twice as many missiles are calculated to need repair, and each repair costs about fifty percent more than before. The other elements of missile maintenance costs also increase.

In addition to raising O&S costs, the degraded reliability and maintainability characteristics have a severe impact on missile hardware readiness levels, as shown in Table 3-12. The lower readiness is the result of two factors. First, more missiles are undergoing maintenance, or are in transit to be repaired. Secondly, the missiles which are available for operations are much less likely to be in good condition than in the base case. The degraded reliability and maintainability characteristics have reduced readiness by 21%, while increasing total life-cycle costs by about four percent from the base case. Table 3-13 summarizes these results.

DEGRADED R&M CASE O&S SPENDING

Annual O&S Costs ($000)

		MPN	O&MN	WPN	Base Case O&MN
Handling & Inspection		800			
Operational Training		40	160		160
IMA		207	1136		738
Depot			1820		552
Supply Support			28		18
Quality Evaluation			302		192
Transportation			28		13
RSSI			73		68
Replacement Training		250	124		124
Spares				287	
Total	$5255	1297	3671	287	
Base Case	3236	1243	1865	128	

TABLE 3-11. Degraded R&M Case O&S Spending

	Poor R&M	Base Case
Total Life-Cycle Hardware Readiness	13,078	16,637
1990 Percentage Readiness	89.3%	91.6%
1990 Percentage Likely Readiness	58.9%	75.6%

TABLE 3-12. Degraded R&M Case Readiness

			Change from Base
Life-Cycle Hardware Readiness		13,078	-21%
Life-Cycle Cost ($M)		$420.71	4%
RDT&E	90.48		
Procurement	290.09		
O&S	40.14	62%	

TABLE 3-13. Degraded R&M Case Summary

3.2.3. T&E Delays, Procurement Stretched Out

The cost-estimating model can also be used to investigate the impact of RDT&E and procurement delays on life-cycle costs and readiness levels. For this projection, it is assumed that the missile program is delayed for six months during both TECHEVAL and OPEVAL. Six-month delays are introduced, as inputs, into these two phases of T&E. In addition, for the first three years of procurement, the procurement rate is reduced by one-third from the base case. The "lost" missiles are reprogrammed for the end of the procurement span, which thus extends longer than the five years of the base case. The same total number, 3120, is procured, and all other inputs remain the same as in the base case.

The delays during T&E and procurement increase the estimated costs of those activities, as shown in Table 3-14. During the T&E delays, R&D spending is calculated to continue at its current rate, in order to overcome the problems encountered in T&E. Thus, the overall cost of RDT&E rises, by about 19% over the base case. Because of the stretched-out procurement time span, fixed costs have to be incurred over a longer period of time, and procurement costs rise about four percent over the base case. Operations and support costs are actually reduced about twelve percent, simply because the simulated introduction and rate of deployment of the missile have been delayed. The annual rate of spending for O&S in the final year of the time horizon, 1990, is essentially identical to the base case.

Similarly, annual measures of readiness for this projection are nearly identical to the base case, once all the missiles have been procured. The life-cycle hardware readiness, however, is much reduced because of the later deployment of the missiles. Table 3-15 presents a summary of these results for this projection.

Cumulative Cost Through 1990		Base Case
Total Life-Cycle Cost ($M)	$430.64	$405.34
RDT&E	107.26	90.48
Non-Recurring Prototype	39.53	31.59
Recurring Prototype	2.92	2.43
Support Equipment	10.39	8.65
T&E	10.65	7.09
Data	3.53	2.69
Program Management	10.10	7.91
Pilot Costs	30.13	30.12
Procurement	301.58	290.09
Pilot Costs	15.33	15.33
Non-Recurring Production	70.53	70.53
Recurring Production	215.72	204.23
O&S	21.80	24.78
MPN	9.78	9.97
O&MN	11.08	13.73
WPN	.94	1.08

TABLE 3-14. T&E Delays & Stretch-Out Case

			Change from Base
Life-Cycle Hardware Readiness		12,540	-25%
Life-Cycle Cost ($M)		$430.64	6%
RDT&E	107.26	19%	
Procurement	301.58	4%	
O&S	21.80	-12%	

TABLE 3-15 Delays & Stretch-Out Case Summary

This case may be viewed as an opposite side of the coin from the previous case, degraded reliability and maintainability. T&E results may indicate that the missile being designed will not attain the desired levels of reliability and maintainability. The question then is, to delay the program while the missile is redesigned and improved, or to push ahead with the program and accept an inferior missile. With the inputs and assumptions used for these particular cases, the model projections indicate that to accept the inferior missile would cost less and result in a slightly higher level of life-cycle readiness over the time horizon, as shown in Table 3-16:

	Degraded R&M	Delays
Life-Cycle Hardware Readiness	13,078	12,540
Life-Cycle Cost ($M)	$420.71	430.64

TABLE 3-16. Degraded R&M vs. Delays

These results are, of course, sensitive to the cut-off data of the analysis, which for all estimates presented here is 1990. By that time, the Degraded R&M case exhibits O&S spending two million dollars per year above the base case, and provides several hundred fewer "missile-years" of readiness per year. The Delay and Stretch-out case, on the other hand, shows spending and readiness essentially identical to the base case after the middle 1980's. Figure 3.5 compares the estimated expenditures of the two cases, and Figure 3.6 contrasts their calculated levels of readiness. It can be seen that the Delay and Stretch-out case provides a higher level of readiness, but not until a later point in time than the Degraded R&M case. If the time horizon were pushed back five or ten years, into the 1990's, the relative standing of the two projections would be reversed.

The next section briefly presents the results of a number of sensitivity analyses conducted with the cost-estimating model.

3.3 SENSITIVITY ANALYSES

The model has been used to make alternative projections based on different assumptions regarding a number of the most important inputs. These projections indicate the sensitivity of missile program life-cycle costs and readiness to variations in the input assumptions. The results of these sensitivity analyses are described briefly on the following summary pages. An overall summary of these sensitivity analyses is presented in Section 3.4.

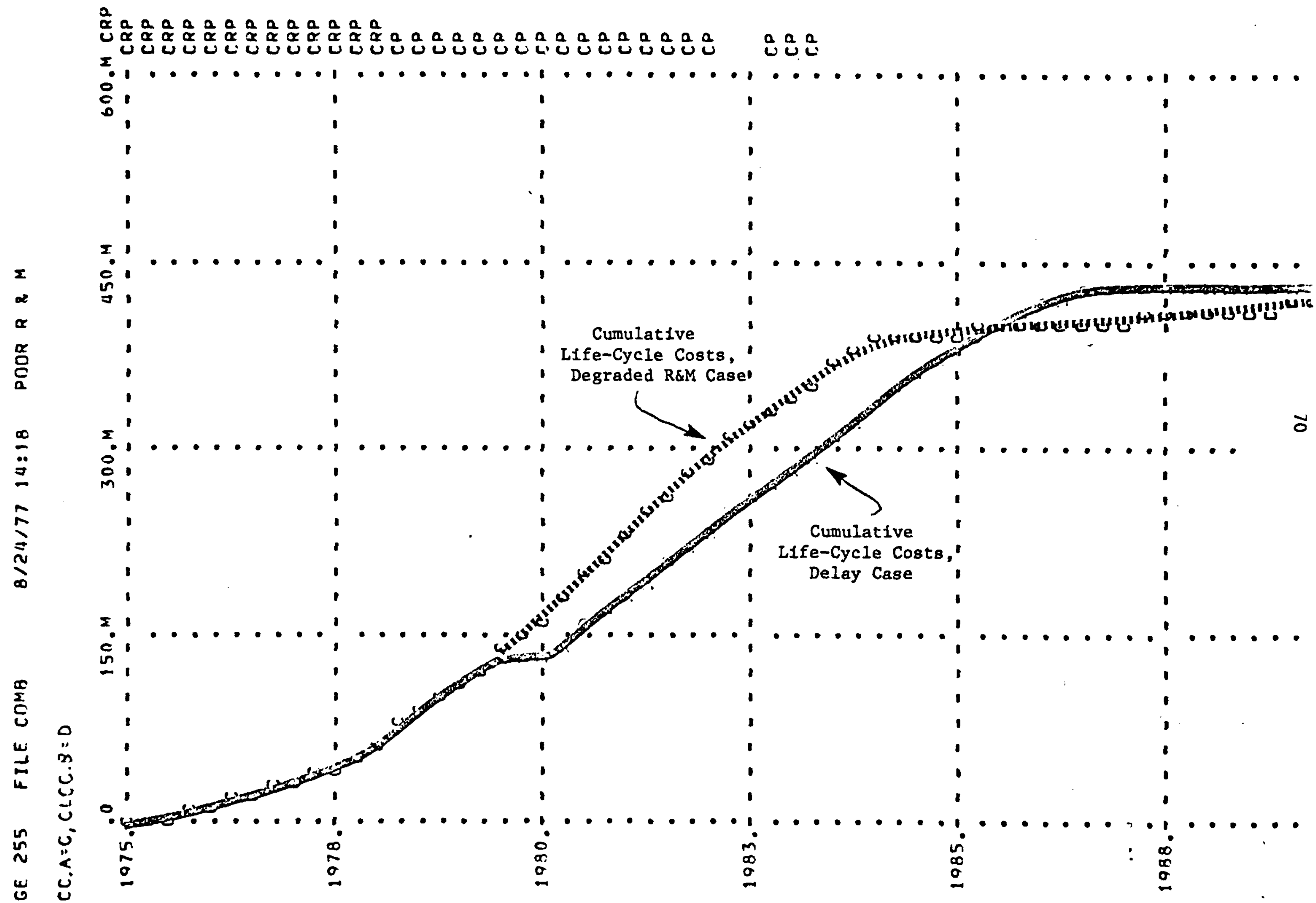

Figure 3.5. Comparative Expenditures

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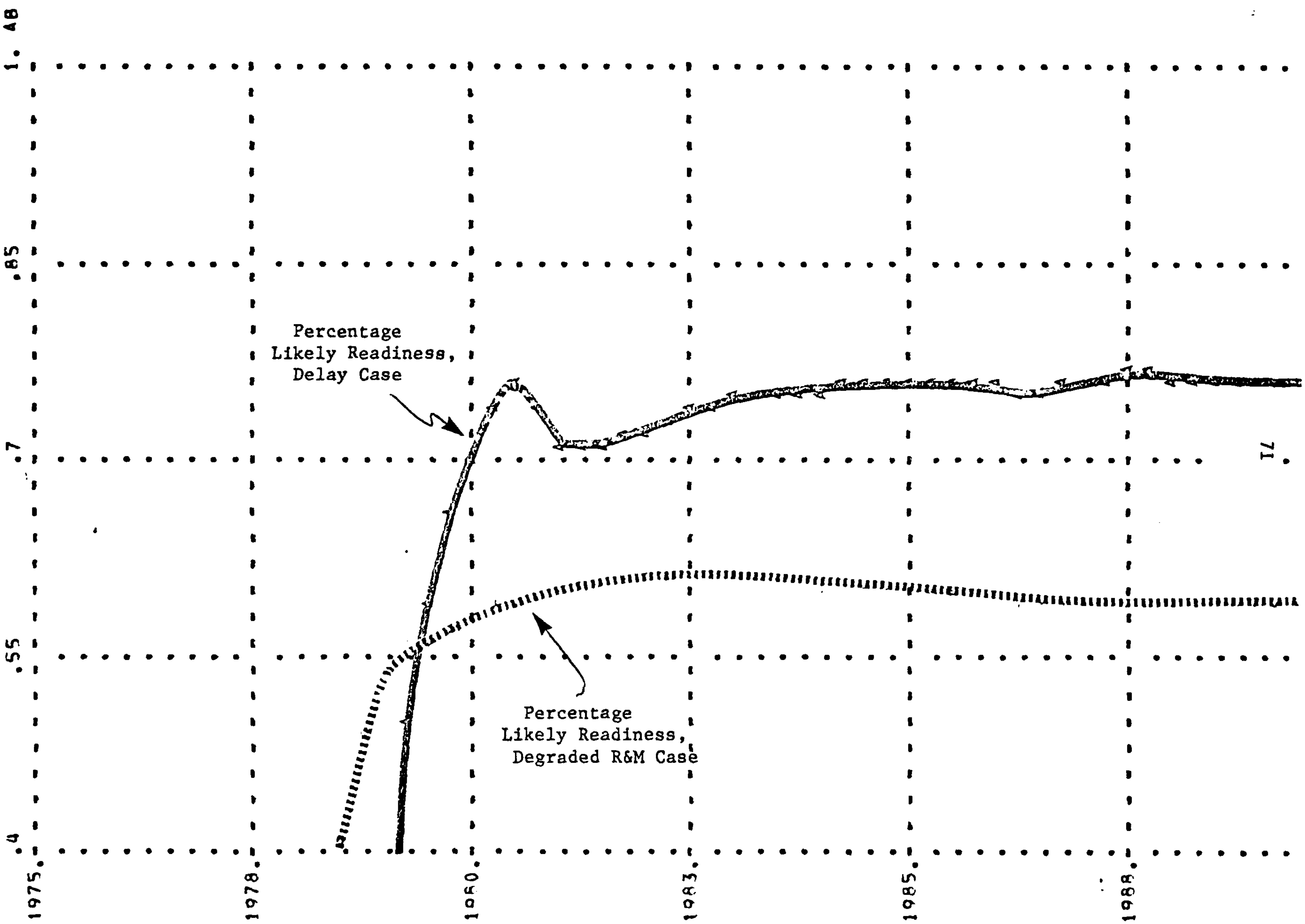

Figure 3.6. Comparative Readiness

AD-A102 139 PUGH-ROBERTS ASSOCIATES INC CAMBRIDGE MA F/G 14/1
DEVELOPMENT OF A DYNAMIC MODEL FOR ANALYSIS AND PLANNING OF LIF--ETC(U)
OCT 77 W R KILLINGSWORTH, W E CUMMINGS N00014-77-C-0047
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3.3.2. Procurement Stretched Out

This projection, again like the alternative case described in Section 3.2.3, assumes that procurement is stretched out over a longer period of time than in the base case. For the first three years, the procurement buys are reduced by one-third from the base case. The "lost" missiles are reprogrammed for the end of the procurement span, so that the total number of missiles procured remains unchanged at 3120. There are no delays during the RDT&E phase, and all other inputs are the same as in the base case.

In this projection, procurement costs are estimated to be about four percent higher than in the base case. This is due to the longer span of time over which the fixed costs of procurement have to be incurred. Operations and support costs through 1990 are reduced about five percent, simply because the rate of deployment of the missiles is slower. Total life-cycle costs have risen about two percent from the base case. Life-cycle readiness is reduced, because for a larger part of the time span under consideration there are fewer missiles deployed and available for operations. Table 3-18 summarizes these results:

PROCUREMENT STRETCHED OUT

				Change from Base
Life-Cycle Hardware Readiness		14,853		-11%
Life-Cycle Cost ($M)		$414.51		2%
RDT&E	90.48			
Procurement	300.52		4%	
O&S	23.51		-5%	

TABLE 3-18

3.3.3. Avionics/BIT "No-Go" Indication Rates

One of the important indicators of missile reliability is the rate at which aircraft avionics or its Built-In Test (BIT) indicates that the missile is not ready for use. For this projection, it is assumed that when the missile is prepared for use, avionics/BIT will give a "no-go" indication twenty percent of the time, rather than ten percent of the time as in the base case. All other model inputs remain unchanged.

For this, as for most analyses of O&S-related factors in a missile program, there is but a slight impact on total life-cycle costs. This is due to the very small fraction of overall life-cycle costs incurred in the O&S phase. Doubling the rate of avionics/BIT "no-go" indications raises projected O&S costs by five percent and total life-cycle costs by just 0.3%. The small size of this increase is caused by the minor impact that the avionics/BIT indication actually has on the missile maintenance workload. Very few of the rounds in the system are actually checked using the BIT or aircraft avionics, just those which are kept "on deck" at the organizational level. Thus, a large change in the avionics/BIT "no-go" indication rate has an impact on just a few missiles. The impact on life-cycle readiness, however, is more severe. Now, roughly twice as amny of the missiles which are kept in deep storage will be rejected when tested by aircraft avionics or the BIT, so life-cycle hardware readiness declines.

AVIONICS/BIT "NO-GO" RATE

				Change from Base
Life-Cycle Hardware Readiness		14,613		-12%
Life-Cycle Cost ($M)		$406.56		0.3%
RDT&E	90.48			
Procurement	290.09			
O&S	26.00		5%	

TABLE 3-19

3.3.4. Shelf Life

A second important component of missile reliability is the rate at which rounds fail while in storage. For this projection, the rate of shelf-life failures is assumed to double from the base base. Now, ten percent of the missiles will have failed after two years at the organizational level (vs. five percent in the base case), and twenty percent of the missiles will have failed after five years in deep storage at reserve magazines (vs. ten percent in the base case). No other inputs have been altered.

The impact of this reliability characteristics on life-cycle costs is greater than an equal percentage change in the avionics/BIT "no-go" indication rate. This is because every missile in the inventory, when it reaches its maintenance due date, is inspected and tested at the IMA. Doubling the shelf-life failure rate raises projected life-cycle O&S costs by eleven percent from the base case. The impact on life-cycle readiness, however, is less severe than when the avionics/BIT "no-go" indication rate is doubled. Since the missiles are regularly rotated back to the IMA for testing and maintenance, many of the missiles are relatively "fresh". It is only after they have been held in storage for some time that the degraded shelf life makes its effect felt on readiness. This is why a more frequent periodic maintenance interval can improve readiness when the missile's shelf life performance is poor, as described in Section 3.2.1. The cost and readiness estimates for this projection are summarized in Table 3-20.

POOR SHELF LIFE

				Change from Base
Life-Cycle Hardware Readiness		15,478		-7%
Life-Cycle Cost ($M)		$408.15		0.7%
RDT&E	90.48			
Procurement	290.09			
O&S	27.59		11%	

TABLE 3-20

3.3.5. Handling Damage

In addition to missile failures, a major source of the workload on the missile maintenance system arises from damage to the missiles during transportation and handling. This projection assumes a doubling of the missile handling damage rate. At each point in the system where handling occurs (at the IMA, on the supply ship, and at the organizational level), four percent of the missiles will be damaged, whereas only two percent were damaged in the base case. All other model inputs remain the same.

The handling damage rate has a serious impact on life-cycle O&S costs, simply because each missile must be handled so frequently in the course of O&S activities. Doubling the handling damage rate increases projected O&S costs by 18%, and raises total life-cycle costs by 1.1%. In contrast, the impact on readiness is less severe than in many of the other analyses. Life-cycle readiness declines by only three percent in this case. This is due to the fact that the entire O&S system is geared towards pushing missiles out to the organizational level. Once they have reached that point, they have passed several hurdles where handling damage can occur. If they are damaged in transit, the system simply repairs them and sends them back out to the fleet, so that only a small additional number undergoing repair are not available for operations.

INCREASED HANDLING DAMAGE

				Change from Base
Life-Cycle Hardware Readiness		16,119		-3%
Life-Cycle Cost ($M)		$409.88		1.1%
RDT&E	90.48			
Procurement	290.09			
O&S	29.32		18%	

TABLE 3-21

3.3.6 Overall Poor Reliability

This projection combines the assumptions of the three cases described above. The rates of avionics/BIT "no-go" indications, shelf life failures, and handling damage are all doubled from the base case. This missile will be less likely to pass avionics/BIT inspection, will deteriorate more rapidly in storage, and will be more susceptible to handling damage than in the base case. No other model inputs are changed.

The estimates of cost and readiness for this projection are, as would be expected, roughly equal to the combination of the three previous estimates. Life-cycle O&S costs are calculated to increase by 36%, and total life-cycle costs by about two percent, from the base case. Life-cycle readiness declines by 21% from the base case.

POOR RELIABILITY

				Change from Base
Life-Cycle Hardware Readiness		13,078		-21%
Life-Cycle Cost ($M)		$414.18		2%
RDT&E	90.48			
Procurement	290.09			
O&S	33.61		36%	

TABLE 3-22

3.3.7. Poor Maintainability

For this projection, the maintenance requirements per missile processed are increased above the base case levels. At the IMA, 25% more manhours are required for each missile handled, and at the depot level, manhours requirements per repair are increased by 50%. No other inputs are changed from the base case.

More maintenance manhours are required for O&S activities, so projected life-cycle O&S costs increase by about fifteen percent from the base case. Total life-cycle costs increase by 0.9%. Readiness levels are not affected. There are no constraints on the level of maintenance effort which can be sustained, so all of the missiles which need repair are in fact repaired. If there were limits which held maintenance manhours below the required level, readiness would decrease as backlogs of unrepaired missiles piled up.

POOR MAINTAINABILITY

				Change from Base
Life-Cycle Hardware Readiness		16,637		
Life-Cycle Cost ($M)		$408.95		0.9%
RDT&E	90.48			
Procurement	290.09			
O&S	28.38		15%	

TABLE 3-23

3.3.8. Rotation of Missiles at Organizational Level

All of the previous applications of the cost-estimating model have assumed that the missiles at the organizational level have been strictly segregated into two groups, one kept ready for use and one kept in deep storage, with no rotation between the two groups. In this projection, it is assumed that rotation between the groups does occur. Missiles are kept "on deck", ready for use, for a period of six months. Then, if they have not been fired in operational training, failed an avionics or BIT inspection, or reached their maintenance due dates, they are returned to deep storage. All other O&S policies, missile R&M characteristics, and other model inputs are the same as in the base case.

Instituting this policy of missile rotation at the organizational level has a very slight detrimental impact on life-cycle cost and readiness. Increased handling damage, due to the extra handling of the missiles when they are rotated, is the major factor causing these effects. Since the number of missiles kept ready for use is relatively small, few missiles are actually involved in the rotation, so the overall impact of the changed policy is very minor.

ROTATION POLICY

				Change from Base
Life-Cycle Hardware Readiness		16,632		-0.03%
Life-Cycle Cost		$405.89		0.1%
RDT&E	90.48			
Procurement	290.09			
O&S	25.34		2%	

TABLE 3-24

3.3.9 100% Supply Availability

The base case projection assumed that only 85% of the needed consumable materials and reparable parts were on hand or immediately available for maintenance activities. This projection assumes that 100% of the needed supplies are immediately available. All other model inputs are identical to the base case.

With this policy, projected readiness is slightly improved at the penalty of slightly increased O&S and life-cycle costs. Because all of the needed supplies are immediately available, maintenance backlogs are reduced, making more missiles available for use. Life-cycle readiness rises by two percent, in comparison with an increase of one percent in O&S costs.

100% SUPPLY AVAILABILITY

				Change from Base
Life-Cycle Hardware Readiness		16,976		2%
Life-Cycle Cost ($M)		$405.63		0.1%
RDT&E	90.48			
Procurement	290.09			
O&S	25.06		1%	

TABLE 3-25

3.3.10 Increased Other Business Base

Among the cost factors taken into account by the Procurement sector of the model is the other direct business base of the missile contractor. The higher the other business base, the less fixed overhead cost has to be borne by the missile program. In the base case projection, the other business base of the contractor was assumed to be $12 million in direct costs per year, roughly equal to the direct costs of the missile program during a year of full-scale procurement. This projection assumes that the other business base doubles in size, to $24 million per year, after the pilot production lot is completed. Thus, overhead costs will decline in full-scale production.

With this change, projected total procurement costs are reduced by about eight percent from the base case. O&S costs also decline by a small amount, since the cost of spares is lower. Total life-cycle costs are about six percent lower than in the base case. Life-cycle readiness is unaffected.

INCREASED OTHER BUSINESS BASE

				Change from Base
Life-Cycle Hardware Readiness		16,637		
Life-Cycle Cost ($M)		$382.35		-6%
RDT&E	90.48			
Procurement	267.20		-8%	
O&S	24.67		-0.4%	

TABLE 3-26

3.3.11 Better All-Around Missile

This projection illustrates the capability of the cost-estimating model for handling the interactions of multiple diverse alternative assumptions regarding the missile program. In this projection, a higher level of R&D effort is assumed to result in a less expensive, more reliable, and more maintainable missile. The basic RDT&E cost factors are increased by twenty percent from the base case, although the RDT&E phase is still assumed to span a period of four years. In procurement, the first-unit direct cost, other unit direct costs, and fixed direct costs are reduced by ten percent from the base case levels. Because of the better missile reliability, the avionics/BIT "no-go" indication rate is reduced from ten percent to five percent. The improved maintainability is reflected by a fifteen percent reduction in the number of man-hours required per missile at the IMA, and a 25% reduction in the labor required per repair at the depot level. All other model inputs remain the same as in the base case.

These changes result in a projected decrease in total life-cycle costs of about four percent, and about a six percent increase in life-cycle readiness. RDT&E costs are calculated to increase by ten percent. This is less than the twenty percent increase in the basic RDT&E cost factors for two reasons. First, the RDT&E budget category includes a large fraction of pilot production spending, which is projected to decline. Secondly, the estimate of RDT&E costs is based upon total missile hardware production costs. Since these are lower than in the base case, RDT&E costs are held down.

Procurement costs decline by eight percent from the base case. This

is less than the ten percent reduction assumed in the direct cost elements because overhead costs do not decline as much as the direct costs. O&S costs over the program life cycle are reduced by some eleven percent, due to the fewer missile failures, lower man-hour repair requirements, and lower spare costs. Life-cycle readiness improves by six percent, since more missiles are available for operations and they are more likely to pass the avionics/BIT inspections. These results are summarized in Table 3-27.

BETTER MISSILE

				Change from Base
Life-Cycle Hardware Readiness		17,656		6%
Life-Cycle Cost ($M)		$387.87		-4%
RDT&E	99.10		10%	
Procurement	266.62		-8%	
O&S	22.16		-11%	

TABLE 3-27

The next section reviews the results of these sensitivity analyses and indicates the points where the cost and readiness estimates are most sensitive.

3.4. IDENTIFICATION OF SENSITIVE POINTS

The sensitivity analyses described in the preceding section, besides illustrating the capability of the estimating technique to answer various kinds of "what-if" questions, have two major purposes. By indicating the points where the cost and readiness estimates are most sensitive to changes in the input assumptions, they suggest areas where further refinement of the model may improve its capabilities. Secondly, they demonstrate the points where the accuracy of input data is most crucial with regard to the accuracy of the estimates provided by the model. Data collection, verification, and analysis may thus be guided by these indications.

Table 3.27 presents, in summary form, a review of the results of the major independent sensitivity analyses which have been conducted with the cost-estimating model. For each analysis, the changes in life-cycle readiness and in the major categories of life-cycle costs are listed. The analyses are presented in three groups, dealing with i) RDT&E and procurement (T&E Delays, Procurement Stretched Out, and Increased Other Business Base), ii) the reliability and maintainability characteristics of the missile (Avionics/BIT "No-Go" Rate, Shelf Life, Handling Damage, and Maintainability), iii) alternative operations and support policies (Rotation at the organizational level, 100% Supply Availability, and Annual Maintenance Due Date), and iv) combinations of factors.

Extensive analyses of the RDT&E and procurement sensitive points have not been conducted simply because these sectors of the model are based in large part upon cost-estimating relationships and formulations already familiar to OP-96D. The analyses presented here do, however, emphasize

SENSITIVITY ANALYSES

% Change From Base

Analysis	Life-Cycle Readiness	Life-Cycle Costs: Total	RDT&E	Procurement	O&S
RDT&E & Procurement					
T&E Delays (3.3.1)	-14	4	19	0.4	-7
Procurement Stretched Out (3.3.2)	-11	2	0	4	-5
Business Base (3.3.10)	0	-6	0	-8	-0.4
Degraded R&M					
BIT/Avionics "No-Go" (3.3.3)	-12	0.3	0	0	5
Shelf Life (3.3.4)	-7	0.7	0	0	11
Handling Damage (3.3.5)	-3	1.1	0	0	18
Maintainability (3.3.7)	0	0.9	0	0	15
O&S Policies					
Rotation (3.3.8)	-0.03	0.1	0	0	2
100% Supply (3.3.9)	2	0.1	0	0	1
Annual MDD (3.2.1)	-3	2	0	0	32
Combinations					
Degraded Reliability (3.3.6)	-21	2	0	0	36
Degraded R&M (3.2.2)	-21	4	0	0	62
T&E Delays, Procurement Stretched Out (3.2.3)	-25	6	19	4	-12

TABLE 3-28

importance of RDT&E and procurement costs in total life-cycle costs. For a Navy air-launched missile program, these are likely to amount to over 90% of total life-cycle costs. Delays in RDT&E, rescheduling out of procurement, and changes in procurement cost factors have a significant impact on total life-cycle costs. Furthermore, a slippage in program schedule results in a period of time in which there are fewer missiles available for use, thus reducing total life-cycle hardware readiness.

Missile reliability and maintainability characteristics may have a significant effect on readiness and on O&S costs without much affecting total life-cycle costs, simply because O&S costs are such a small fraction of total costs for the missile program. For the "average" missile represented in the base case, in increasing order of importance, the handling damage rate, the shelf life failure rate, and the avionics/BIT "no-go" indication rate have a negative impact on missile hardware readiness. Their impact on O&S and total life-cycle costs, however, is in the reverse order. Thus, a avionics/BIT "no-go" indication rate has a large impact on readiness but only a minor impact on costs, while the handling damage rate affects costs much more relative to its impact on readiness. Missile maintainability may not have much effect on readiness, if there are no constraints in commiting resources to missile maintenance, but it does have a sizable impact on costs.

A policy of rotating the missiles at the organizational level has only a minor effect, decreasing readiness marginally while costing slightly more. 100% supply availability, as would be expected, increases both readiness and costs, but only slightly. The maintenance due data policy is seen to be a more important determinant of life-cycle costs and readiness. For the missile represented by the base case assumptions, more frequent periodic

maintenance adds significantly to costs and actually decreases readiness. As was seen in Section 2.3.1, however, more frequent periodic maintenance may improve readiness when the missile has a poor shelf life performance. This result emphasizes the importance of analyzing how well the missile maintenance concept is tailored to the specific physical characteristics of the missile.

In summation, these analyses indicate the relative sensitivity of the cost and readiness estimates to these RDT&E, procurement, and O&S factors. The RDT&E and procurement impacts are especially important, since these costs make up the bulk of total missile program life-cycle costs. In the O&S sphere, the handling damage and shelf life failure rates, particularly in conjunction with the maintenance philosophy in use, are crucial factors underlying O&S costs. Other missile reliability characteristics, such as the avionics/BIT "no-go" indication rate, will have more of an impact on readiness but less on total costs.

IV. SUMMARY, CONCLUSIONS, AND NEXT STEPS

The objective of the effort described in this report was to examine the feasibility of using the system dynamics methodology for estimating operating and support and life-cycle costs. The feasibility was to be considered by attempting i) to develop an O&S cost estimation technique for Navy air-launched missiles based on cost-driving factors such as reliability and maintainability characteristics and maintenance procedures, and ii) if successful in such an effort, to integrate the O&S technique with existing techniques for estimating RDT&E and procurement costs. Both of these tasks have been successfully completed and indicate that system dynamics is highly suited for use in cost estimation. A cost estimation technique designed for Navy air-launched missile programs has been developed with the following capabilities:

i. Calculates an estimate of annual program spending by life-cycle phase (RDT&E, procurement, and O&S) and budget category;

ii. Cumulates annual program expenditures into an estimate for overall direct life-cycle cost;

iii. Calculates annual expenditures and life-cycle cost for alternative procurement rates, reliability and maintainability characteristics, and operations policies; and

iv. Demonstrates trade-offs between procurement costs, reliability and maintainability, readiness, and life-cycle costs.

The technique has been quantified for a representative Navy air-launched missile program and used to calculate cost estimates for the following cases: i) a benchmark base case, ii) an alternative maintenance concept, iii) different reliability and maintainability characteristics, and iv) delays occurring during T&E. Numerous sensitivity analyses have also been conducted.

Although the analysis was conducted using representative input numbers, not those of a specific program, some useful general indications are obtained for the components of air-launched missile life-cycle costs. Specifically, in this case for air-launched missiles, RDT&E contributes approximately 20-25% of life-cycle cost, procurement represents 70-75%, and O&S only 5-10%. Consequently, since air-launched missile O&S costs are such a small factor of program life-cycle costs, factors effecting O&S costs tend not to have a major impact on life-cycle costs, although meaningful trade-offs are potentially available.

Because of the highly successful feasibility analysis that has been completed, several next steps are currently being undertaken. First, the technique is being quantified with carefully developed inputs for a specific Navy air-launched missile program. This will provide several major and immediate benefits. It enables the estimates generated by the technique to be compared for validity purposes with existing estimates based largely on subjective interpretations of past experiences. The quantification will provide insights into data collection requirements and difficulties. Finally, this step will enable the program manager to investigate trade-offs that otherwise were virtually impossible. The second step being undertaken is the preparation of a training program in the use and modification of the technique. This program will be presented to OPNAV analysts so that the technique will become an effective and efficient in-house tool.

Finally, another step being taken is the development of a similar cost estimation technique for Navy aircraft programs. This will focus on the much more complex aircraft O&S system, the multitude of costs involved, and, because of the much larger O&S costs, the significant design and operating trade-offs available to program managers.

APPENDIX A

COST-ESTIMATING RELATIONSHIPS

This Appendix contains a set of tables presenting details of the cost-estimating relationships used in the RDT&E and Procurement Sectors of the model. A table presenting details of the cost-estimating equations for the O&S sector is also included.

Table A-1. RDT&E CER's

COST ELEMENT	VARIABLE NAME	CER (thousands of FY77$)
Nonrecurring Prototype	NRPOBC	$\ln(NRPOBC) = 10.339 + .0027\ (CAC)$
Recurring Prototype	RPOBC	$RPOBC = 2905 + 6.21\ (CAC \times PON^{0.8156})$
Test and Evaluation	TEBC	$TEBC = 3.7327 \times (CAC \times PNT)^{0.9026}$
Support Equipment	RDSEBC	$RDSEBC = 1705 \times (CAC)^{0.4072}$
Data	RDDABC	$RDDABC = 26.64 \times (NRPOBC + RPOBC + TEBC + RDSEBC)^{0.4519}$
System Engineering/ Program Management	RSPMBC	$RSPMBC = 2.95 \times (NRPOBC + RPOBC + TEBC + RDSEBC + RDDABC)^{0.7495}$

INPUT VARIABLES	
CAC	Average unit hardware cost of first 1000 missiles
PON	Number of prototype missiles
PNT	Number of test units for T&E

Table A-2. RECURRING PROCUREMENT MODEL

Formulation:

Unit Recurring Cost = (Direct Cost) x (Overhead Factor) .

$$\text{Direct Cost} = a\,x_i^{\,b} + \frac{k_3}{R} + k_4$$

$$\text{Overhead Factor} = 1 + k_2 + \frac{k_1}{(R \times \text{Direct Cost}) + B}$$

$$\text{Annual Procurement Spending} = \text{Annual Direct Costs} + \text{Annual Overhead Costs}$$

$$\text{Annual Direct Costs} = k_3 + Rk_4 + \frac{a}{b+1}\left[(n+R)^{b+1} - n^{b-1}\right]$$

$$\text{Annual Overhead Costs} = k_2 + \left[\frac{k_1}{\text{Annual Direct Costs} + B}\right]\left[\text{Annual Direct Costs}\right]$$

Inputs

a = first-unit costs

x_i = cumulative production quantity

b = slope of log-linear cost-improvement curve

R = annual production

k_3 = fixed direct costs

k_4 = variable (non-learning) direct costs

k_1 = fixed overhead costs

k_2 = variable overhead rate

B = total direct charges on other business

n = cumulative production at beginning of year

Table A-3. NONRECURRING PROCUREMENT CER's

COST ELEMENT	VARIABLE NAME	CER *(thousands of FY77$)*
Initial Tooling and Test Equipment	SITTEC	$SITTEC = 1.86 \times (CAC)^{0.51} \times (PRR/12)^{0.06}$
		CER (thousands of FY77$)
Support Hardware	SPTHWC	$SPTHWC = 0.00004 \times (OHP)^{2.50}/(QUAN)^{0.17}$
Spares	SPAREC	$SPAREC = 0.045 \times OHP$
Aggregate Level Support	ALSC	$ALSC = 1.51 \times (OHP)^{0.65} \times (QUAN)^{0.01}$
(or)		
Disaggregated Support	DALSC	$DALSC = SPTPMC + F2OTEC + TSEC + DATAC + ECPOC$
Support Engineering/ Program Management	SPTPMC	$SPTPMC = 0.43 \times (OHP)^{0.67} \times (QUAN)^{0.11}$
Follow-On OT&E	F2OTEC	$F2OTEC = 0.055 \times ALSC$
Training Services and Equipment	TSEC	$TSEC = 0.00062 \times (OHP)^{0.95} \times (QUAN)^{0.42}$
Data	DATAC	$DATAC = 0.69 \times (OHP)^{1.44} / (QUAN)^{0.69}$
ECP's/ECO's	ECPOC	$ECPOC = 0.00013 \times (OHP)^{2.27} / (QUAN)^{0.17}$

Table A-3. NONRECURRING PROCUREMENT CER's

(continued)

INPUT VARIABLES	
CAC	Average unit hardware cost of first 1000 missiles (000 FY77$)
PPR	Annual peak production rate
OHP	Total cost of missile hardware production ($M)
QUAN	Total number of missiles produced

Table A-4. O&S COST CALCULATIONS

COST ELEMENT	CALCULATION
Handling and Inspection	(Number of Men) x (Cost per Man per Year)
Operational Training	(Number of Training Firings) x (Cost per Firing)
IMA Maintenance:	
Maintenance Assembly Labor	(Number of Missiles Assembled) x (Manhours per Assembly) x (Cost per Manhour)
Missile Testing Labor	(Number of Missiles Tested) x (Manhours per Test) x (Cost per Manhour)
Missile Disassembly Labor	(Number of Missiles Disassembled) x (Manhours per Disassembly) x (Cost per Manhour)
Consumable Materials	(Assemblies) x (Consumables Usage) + (Tests) x (Consumables Usage) + (Disassemblies) x (Consumables Usage)
Overhead	(Total IMA Labor Costs) x (IMA Overhead Rate)
Depot Maintenance:	
Missile Section Repair Labor	(Number of Sections Repaired) x (Manhours per Repair) x (Cost per Manhour)
Reparables Repair Labor	(Number of Reparables Repaired) x (Manhours per Repair) x (Cost per Manhour)
Consumable Materials	(Sections Repaired) x (Consumables Usage) + (Reparables Repaired) x (Consumables Usage)
Overhead	(Total Depot Labor Costs) x (Depot Overhead Rate)

Table A-4. O&S COSTS CALCULATIONS
(continued)

COST ELEMENT	CALCULATION
Supply Support	(Total Consumables Used) x (% of Consumables Costs) + (Replenishment Spares Cost) x (% of Reparables Costs)
Quality Evaluation:	
Labor	(Number of Missiles Evaluated) x (Manhours per Evaluation) x (Cost per IMA Manhour)
Consumable Materials	(Number of Missiles Evaluated) x (Consumables Usage)
Overhead	(Quality Evaluation Labor Cost) x (IMA Overhead Rate)
Transportation	(Sections to and From Depot) x (Containerized Weight) x (Distance Shipped) x (Cost per Ton-Mile)
RSSI	(Rounds to and From IMA) x (Containerized Weight) x (Cost per Ton)
Replacement Training	(Manpower Level) x (Cost Per Man) ÷ (Average Turnover Time)
Replenishment Spares	(Number of Reparables Used) x (Average Cost per Reparable)

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